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Collision of comet Shoemaker – Levy 9 with Jupiter: what shall we see?

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Abstract. In July 1994 a dramatic cosmic event will take place: comet Shoemaker – Levy 9 will collide with Jupiter. The entry of the comet into the atmosphere of Jupiter will be accompanied by a rapid energy release and an explosion will take place. The energy released during the explosion, of the order of 10^7 Mt, will exceed by some thousandfold the total nuclear potential accumulated by mankind. Some characteristics of the interaction of the comet with Jupiter are discussed and possible consequences of the collision are outlined.

1. Introduction

On 16 July 1994 at 22:30 Moscow time the first fragment of comet Shoemaker – Levy 9 will enter the dense atmospheric layers of Jupiter [2]. Other authors predict that this event will take place two days later, on 18 July 1994 [3 – 7]; however, we are sure that this is not a fundamental disagreement because telescopes throughout the world (including the orbital Hubble Space Telescope) will be aimed at Jupiter long in advance of the collision.

Thorough observations and studies of comet Shoemaker – Levy 9 were started just after its discovery on 24 March 1993; papers devoted to this comet began to appear almost daily. News of the forthcoming collision of the comet with Jupiter has reached television and the pages of all major newspapers around the world.

Why is an event that will happen so far away from us, at a distance of about 600 million kilometers, of such general interest? One can attribute this not only to the fact that mankind has been interested in events occurring in space since ancient times, but also that events like this one may become a tragic reality for Earth.

Collision of a similar comet or an asteroid with Earth is highly improbable; according to estimates [8], such an event takes place once in a million years. However, we cannot predict precisely when this will happen: maybe in a million years, but it cannot be excluded that it will occur this century. One must keep in mind that comet Shoemaker – Levy was discovered only 16 months before its impending collision with Jupiter.

Collision of a similar comet with Earth would have catastrophic consequences: the predicted yield of the explosion of comet Shoemaker – Levy as it ploughs into the Jovian atmosphere is $\sim 10^{22-24}$ J or $\sim 10^{6-8}$ Mt. This exceeds ten thousand times the total nuclear potential accumulated by mankind and corresponds to approximately 250 million Hiroshima bombs. It is widely assumed that a collision of a large asteroid or a comet with Earth (diameter $D \sim 10$ km, energy released during explosion $\sim 10^{24}$ J or $\sim 10^8$ Mt) 65 million years ago resulted in dust pollution of the atmosphere leading to a climate change and the extinction of Mesozoic groups of animals [9 – 10]. We note also that the yield of the explosion of the well-known Tunguska meteorite (with a diameter of ~ 30 m) is estimated at about 30 – 50 Mt, that is a million

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times less than that of the explosion of comet Shoemaker–Levy. According to the same estimates [8], Tunguska-like meteorites strike Earth once in 200–300 years.

So it is necessary to understand the process of such collisions and what are their consequences for planets of the solar system. From this point of view, the collision of comet Shoemaker–Levy with Jupiter can provide important information not only about Jupiter, but in general about the nature of explosive interactions of large comets and meteors with the atmospheres of planets. This information may turn out to be essential in the future.

Thus, it can be argued that scientists have not had such a valuable object to investigate since the fall of the meteorite on Tunguska. Unfortunately, the collision will take place on the far side of Jupiter, so direct visual observations of the event will be impossible and the question is what data do we need for reconstructing the event.

In the present paper, many of the processes are not examined rigorously because the collision of comet Shoemaker–Levy with Jupiter involves such an extensive range of physics that a detailed description of the event is beyond the scope of a journal article.

Many professional astronomers plan to observe the outcome of the collision. One of the most promising observational plans undertaken from the territory of the FSU is a programme initiated by the International Institute of Asteroid Safety Problems (St Petersburg) under an RFFR (Russian Fund for Fundamental Research) grant (Table 1).

Owing to the faintness of the object, observations of the collision are expected to be quite difficult even with the techniques mentioned above. This increases the importance of having a reliable ephemeris of comet Shoemaker–Levy and a model of its collision with Jupiter. The initial results obtained in this direction are described below.

2. Preliminary data

The diameter of the comet has already been determined as about 10 km at the very beginning of its astronomical observations [1]. Now the comet is known to be extensively fragmented. Presumably, it has been broken up by tidal forces on its close approach to Jupiter [2, 11]. According to observational data, the comet consists of about 20 parts, the largest of them being from 1 to 10 km across [1–7]. Collisions of the comet fragments with Jupiter will continue for almost a week: from 16 till 21 July [2] or, according to other predictions [6–7], from 18 till 24 July. The collision itself is best represented as bombarding Jupiter with blocks of ice (with cosmic dust grains embedded in them), falling onto Jupiter's surface at an angle of about 45° and with a speed $v_i \approx 64-65$ km s^{-1}. The comet bulk density and block sizes appear to vary in the range $\rho_i \sim 0.3-3$ g cm^{-1} and $D_i \sim 0.3-3$ km, respectively. At present only the impact velocity has been determined reliably, and the uncertainties in the comet bulk density and fragment sizes lead to a substantial uncertainty (up to two orders of magnitude) in estimates of the masses and kinetic energies of the fragments.

Because of the rapid rotation velocity of Jupiter (the period of rotation is about 10 h) and the long duration of the collision process, one should expect the explosions to occur in different regions of the Jovian atmosphere.

Table 1.

Organization	Instrument	Observational task
Special Astrophysical Observatory, RAS	6-m telescope	Superhigh resolution spectroscopy, fast photometry
Main Astronomical Observatory, RAS	MTM-500 (Mt Assy-Turgen', Kazakhstan)	Spectroscopy, spectrophotometry
	photometer–polarimeter	eight-colour (UBV RIJHK) photometry and polarimetry
Kislovodsk Station of the Main Astronomical Observatory	FP-ZU photometer–polarimeter on 1-m telescope	Photometry, spectroscopy, IR-observations
Shternberg Astronomical Institute	1.5-m telescope Mt Maidanak, Uzbekistan)	Photometry, spectroscopy
	0.6-m telescope (Crimea, Ukraine)	photometry, spectroscopy
Crimean Astrophysical Observatory	0.4-m double astrograph (Crimea, Ukraine)	Astrometry
	1.2-m telescope (Crimea, Ukraine)	Spectroscopy, polarimetry
	2.6-m telescope (Crimea, Ukraine)	Shain Telescope CCD-observations,
Radioastronomical Institute, Ukraine Academy of Sciences	25-m radiotelescope (Kharkov, Ukraine)	Imaging radio-observations at 10–25 MHz

If one takes into account that the comet fragments are of different sizes and the energy release occurs at different altitudes, there is a unique opportunity to explore the two-dimensional structure of the Jovian atmosphere, in longitude and in altitude. In particular, this enables one to study the stability of large-scale flows on Jupiter. We note that the energy of the vortex motion of the Great Red Spot of Jupiter ($\sim 10^{26}$ erg s^{-1} [12]) is inferior to the energy of explosion of a rather small fragment ($D_i \sim 100$ m).

The process of braking of a separate comet fragment can be quantitatively represented as follows. A noticeable braking action begins when the mass of the atmosphere replaced by the fragment matches the mass of the fragment. The braking of the fragment in an exponential atmosphere [$\rho(h) \approx \rho_0 \exp -h/H(h)$], where H is a so-called scale of homogeneous atmosphere] leads to the bulk of the kinetic energy being released in a column of gas of height $\sim H$ with a cross section $\sim D_i^2$.

In the Jovian atmosphere at altitudes where the largest fragments of the comet are braked, $H \approx 50$ km. Since a substantial portion of the kinetic energy of the fragment is released on time scales $\tau \sim H/v_i \approx 1$ s, the braking of the fragment in the Jovian atmosphere is of an explosive nature.

In papers which appeared just after the probability of the collision of the comet with Jupiter had been judged to be high [13–15], the first minutes after the explosion of a separate fragment were considered; that is, short-living perturbations were studied. As a rule, the parameters of the optical flash that accompanies the explosion and the cloud behaviour in an early stage were analyzed. We note a strong scatter in the results of numerical calculations; for example, the pressure of the atmospheric gas at which explosion occurs has varied, depending on the drag model assumed, from about 100 bar to 50 mbar. This corresponds to a range of altitudes from -250 to 100 km in the Jovian atmosphere.†

The diversity of these results may be of fundamental nature, since the cloud layer screening optical radiation is located at altitudes of ~ 0 to ~ 40 km.

As we already mentioned, the process of collision as such will not be seen from Earth, because fragments of the comet will fall onto the far side of Jupiter; the predicted site where the fragments will fall corresponds to about 45° of southern latitude. Since the rotational period of Jupiter is about 10 h, the site of the impact will be seen about one hour later. Where the impact takes place near the terminator (the boundary dividing the light and dark sides of the planet), this time difference can be smaller.

In this connection here is particular interest in searches for long-living consequences of the collision that can be studied by radiophysical and optical facilities, both ground-based and orbital. The process of the collision of comet Shoemaker–Levy with Jupiter will be monitored by the Hubble Space Telescope; in particular, it can register electromagnetic radiation unavailable to ground-based observatories, but which can shed new light on the character of the collision.

Here is a short list of possible observable consequences of the collision of comet Shoemaker – Levy with Jupiter, which will be discussed below:

— formation in the Jovian atmosphere of long-lived vortex structures with a size of the order of a thousand kilometres;

— optical flashes accompanying explosions of the fragments;

— generation of inner gravitational waves by a rising explosion cloud, which will stimulate condensation in the tropo-spheric layers and formation of an abnormal cloud layer;

— ionospheric and magnetospheric perturbations resulting from the comet explosion;

— anomalies of RF emission stemming from radiation belts of Jupiter and, specifically, from a magnetic force tube passing through the explosion site;

— specialfeatures of glow of the ionosphere and the upper atmosphere in optical, IR, and RF bands.

3. Comet Shoemaker – Levy. Historical note

The comet that has excited the wide scientific world was discovered by K S Shoemaker, E M Shoemaker, and D H Levy at the Palomar Observatory on 24 March 1993, and was named 'Comet Shoemaker – Levy 9' [1]. The very first plates with the comet's image showed it to be an unusual comet. The image looked like a band similar to a meteorite trace in the terrestrial atmosphere. The band was nearly $1'$ long. It had no central condensation and was oriented from east to west. The comet had a weak luminous tail. In two nights J V Scotti obtained the image of the comet as a narrow band, $47''$ long and $11''$ wide [3]. He observed at least 5 separate bright fragments in the image. The brightest fragment was discovered approximately $14''$ away from the eastern edge of the linear image of the comet. In the first communication [1] 5 precise astrometrical positions of the comet with reference to the centre of the image were reported. On 27 March J Luu and D Jewitt [4] reported on a study of the comet's image with 17 separate fragments aligned in a $50''$ long band. Their number later increased to 21. At present 19 fragments of this comet stretched as a 'string of pearls' (Fig. 1) are steadily observed [18]. Comet Shoemaker – Levy 9 is a very weak celestial object, its integral magnitude varying within the range 14 – 15. Stellar mag-nitudes of separate fragments are 6 – 7 magnitudes above this value; that is, they reflect approximately 100 times less light than the whole comet does. That is why observations of the separate fragments are possible only by using large

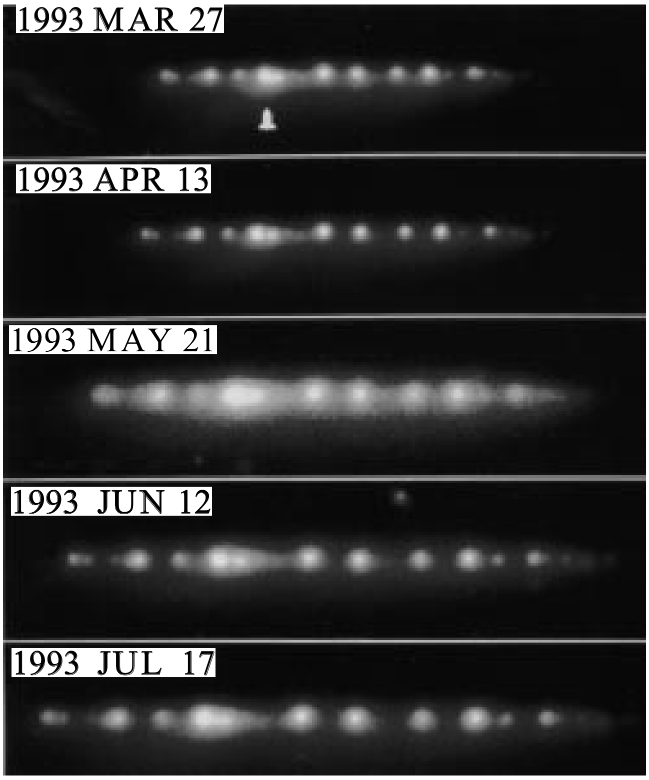

Figure 1. Comet Shoemaker – Levy 9 [18].

Table 2.

Fragment number	Date of impact/UT	Angle of entry/min	Fragment number	Date of impact/UT	Angle of entry/min
21	16.76	44.99	10	—	—
20	17.07	44.85	9	20.37	44.29
19	17.19	44.61	8	20.39	44.15
18	17.41	44.88	7	20.75	44.62
17	17.59	44.67	6	21.17	44.46
16	17.98	44.83	5	21.61	44.62
15	18.26	44.87	4	21.57	44.54
14	18.77	44.88	3	21.87	44.44
13	—	—	2	22.11	44.25
12	19.38	44.73	1	22.27	44.66
11	19.88	44.70			

†Height within the Jovian atmosphere is nominally measured from the level at which the ambient pressure is 1 bar, the same as the atmospheric pressure on Earth. Therefore in the Jovian atmosphere there are 'positive' and 'negative' altitudes.

telescopes equipped with CCD matrices that enable one to detect very weak luminous fluxes. Treatment of the first astrometrical observations of the comet revealed quite a high probability of collision of the comet with Jupiter in 1994. Further refinement of the comet's orbit, together with new observations and information about the orbits of individual fragments, confirmed the likelihood of collision with Jupiter. The dates and angles of entry (between the velocity vector and the local normal) of the fragments on Jupiter's surface are listed in Table 2. Note that the numbering of fragments adopted in the literature is in reverse order of the sequence in which the fragments will fall; the time given is GMT, as fractions of days in July 1994.

The velocity with which the fragments will fall varies within the range 64 – 65 km s^{-1}. Based on the hypothesis about destruction of the comet by tidal forces at the close approach to Jupiter, estimates were made of the sizes of the 8 largest fragments (17, 15, 14, 12, 11, 7, 5, 1) [2]. The maximal size of the fragments turned out to be 1 km. The assumed density of the comet material is 0.3 – 3 g cm^{-3}. Because of uncertainties in the bulk density of the comet, and sizes and shapes of the fragments, the error in the mass (and correspondingly kinetic energy) of any one fragment may be as high as one or two orders of magnitude. Note that the mass of the fragments can be corrected on the basis of photometric observations immediately before they hit Jupiter. Preliminary calculations give the impact site as being located on the far side of Jupiter, at 45° southern latitude. It should be noted that the accepted theory of this enigmatic object is questionable. One current speculation is that this is not a comet (that is, an object that orbits the Sun) captured by Jupiter, but a 'protuberance' ejected by Jupiter about 22 years ago, which in this period of time performed 10 revolutions along an almost polar orbit, and was 'torn' to fragments by tidal forces in the previous loop during a close approach to Jupiter in 1992. Figs 2 – 4 shows a retrospective evolution of jovicentric elements of the 12th fragment, nearest to the centre of the band of the fragments and thus, probably, moving along an orbit that is closest to its progenitor's orbit. Evolution of the pericentric distance is shown in Fig. 2, in which the pericentric distance in units of the mean radius of Jupiter (71 400 km) is shown over the period 1972 – 1994. Evolution of the eccentricity and the orbital inclination to the ecliptic (ecliptic and equator 2000.0) are presented in Figs 3 and 4. The figures show that the orbit of the comet Shoemaker–Levy is unstable, beginning and ending on Jupiter's surface. If these calculations remain qualitatively unchanged after further refinement of the fragments' orbits, they could serve as

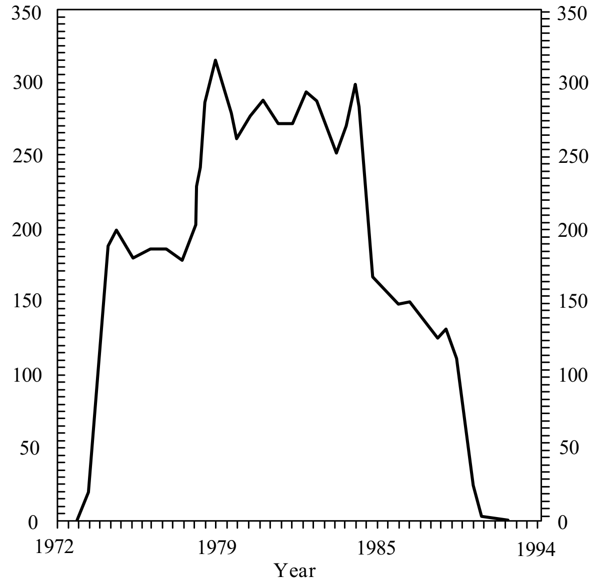

Figure 2. Evolution of the pericentric distance (expressed in units of the mean radius of Jupiter) for the 12th fragment of comet Shoemaker – Levy 9.

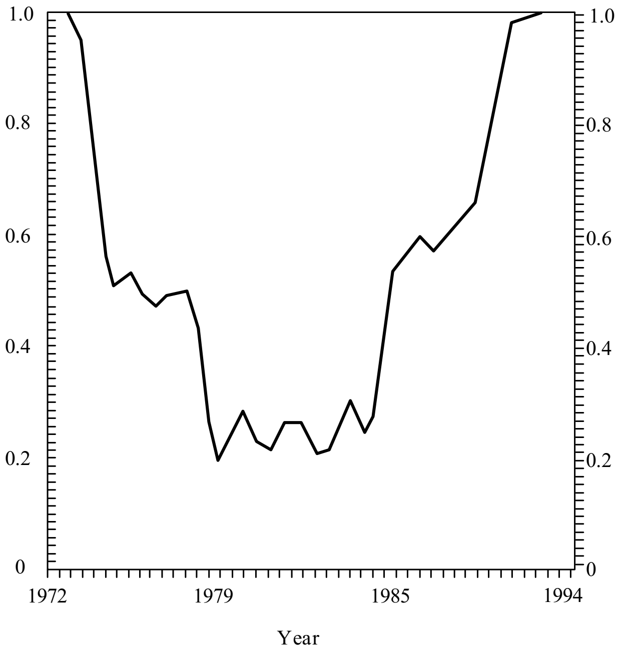

Figure 3. Evolution of the eccentricity for the 12th fragment of comet Shoemaker – Levy 9.

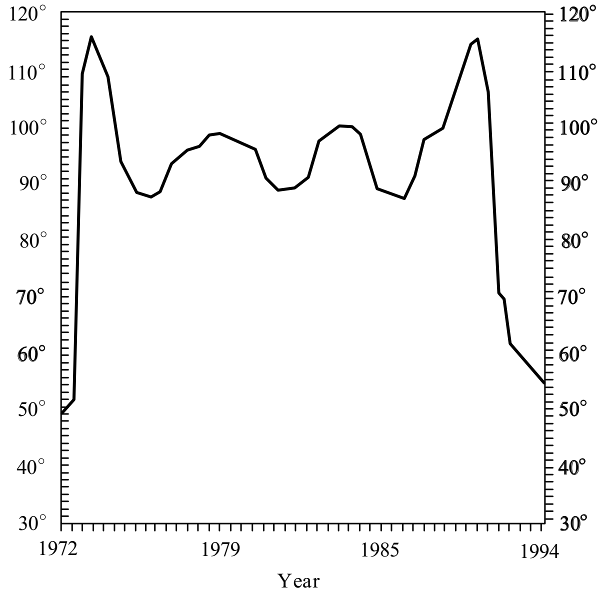

Figure 4. Evolution of the orbital inclination to the ecliptic for the 12th fragment of comet Shoemaker–Levy 9

a confirmation of Vsekhsvyatskii's hypothesis [19, 20] about the origin of short-period comets in the solar system. According to his theory, short-period comets originate inside Jupiter or its satellites, and then are ejected into the solar system as a result of volcanic or some other activity.

Thus, comet Shoemaker – Levy 9 has a complex fragmented structure, the uncertainty in both its size and density being very high. Below we shall try to estimate the scale of the impact of one of the largest fragments as it plunges into the Jovian atmosphere, by using numerical modelling and qualitative considerations. We hope that features of the interaction of the comet with the Jovian atmosphere will be reflected in sufficient detail.

4. Explosion of the comet in the Jovian atmosphere: qualitative features and results of numerical modelling

The density and the pressure of the Jovian atmosphere increase exponentially with depth. The solid fragments of the comet entering it will be subjected to severe mechanical and thermal-radiative loads. In front of a fragment moving at a speed two orders of magnitude greater than the speed of sound in that atmosphere, a jump in the density of the atmospheric gas will occur. A detached shock wave will be located a distance of about one tenth of the characteristic dimension of the solid body. The region between the shock wave and the frontal surface of the fragment — the so-called shock-compressed layer — will be filled in with the atmospheric gas contaminated by vaporized comet matter. The gas pressure in this shock compressed layer reach several thousand atmospheres and the gas will be heated to temperatures of the order of 10 000 K. This is due to the velocity of the gas flow in the central portion of the frontal surface of the comet's fragment being reduced almost to zero.

The gas flow relative to the side faces of the solid compact fragment is characterized by large velocity gradients in the direction normal to the body surface and, consequently, by a significant dissipation of the kinetic energy of the viscous gas, leading to a sharp temperature rise in the gas layers adjacent to the surface and of the solid body itself. The atmospheric gas in this boundary layer, as well as in the shock-compressed layer, will begin to glow, radiating in the optical and infrared bands, whereas the solid fragment will begin to ablate. The amount of mass of the solid body lost in this way will be relatively small, as the propagation velocity of the vaporization front determined by the ratio of energy released in the boundary layer and in the shock-compressed layer to the heat of vaporization of the comet matter does not exceed a fraction of 1 m s^{-1} for the case considered here.

Indeed, an equation widely used in meteoritics that describes the change of the mass of the fragment as it enters the atmosphere is:

$$Q_i \frac{\mathrm{d}M_i}{\mathrm{d}t} = -\frac{1}{2} C_q \rho_h v_i^3 S_i \;, \tag{1}$$

where M_i, v_i, S_i are the mass, velocity, and maximal cross-section area of the comet's fragment, ρ_h is the density of the surrounding Jovian atmosphere, Q_i is the specific heat of vaporization of the fragment's material, and C_q is a dimensionless coefficient describing the heat flux received by the fragment.

If the value of the coefficient C_q is taken as being of the order of 10^{-2} – 10^{-4} [22] because of the low transparency of the mixture of the atmospheric gas with vaporized solid matter, then ice fragments ($\rho_i \sim 1$ g cm^{-3}, $Q_i \sim 10^6$ erg g^{-1}) of about 1 km in diameter moving with velocities $v_i \approx 60$ km s^{-1} would conform to the above estimate.

Eqn (1) also shows that a noticeable ablation-induced decrease in the mass of the fragment will start at heights where the density of the adjacent Jovian atmosphere is $\rho_\mathrm{a} \sim 10^{-5}$ g cm^{-3}, nearly 60 km above the cloud layer. This is important because it would allow us to obtain some information by observing the comet's trace should the products of the comet's explosion be screened by clouds. In particular, a characteristic glow of the comet material may occur in the outer layers of the Jovian atmosphere.

Mechanical loads caused by the shock-compressed layer will be the main factor influencing the fragment's motion. Their action will manifest itself in the form of drag phenomena, breakup, and inelastic (plastic) deformation of the fragment.

Slowing down of the comet fragment in the atmosphere of Jupiter caused by aerodynamic drag can be analyzed by using the simplest equation of motion

$$M_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = -\frac{1}{2} C_x \rho_h v_i^2 S \;, \tag{2}$$

where C_x is a dimensionless drag coefficient [the remaining notation is the same as in Eqn (1)]. A noticeable deceleration begins in the dense atmospheric layers of Jupiter, where the density ρ_h is equal to

$$\rho_h \sim \frac{2 \rho_i D_i \cos\theta}{3 C_x H} \, . \tag{3}$$

Here ρ_i is the density of the comet material, θ is the angle of the comet's entry into the atmosphere (relative to the local vertical), H is the scale height of the Jovian atmosphere at the point of braking. By putting $\rho_i \approx 1$ g cm^{-3}, $D = 1$ km, $\theta = 45°$, $H \sim 75$ km, one finds that the main braking will occur at a density of the surrounding gas of $\rho_\mathrm{s} \times 2 \times 10^{-3}$ g cm^{-3} and a pressure of $p_\mathrm{s} \sim 90$ bar. Note that these parameters correspond to a height of $h_\mathrm{s} \approx -235$ km in the Jovian atmosphere. Therefore, the comet fragment will penetrate significantly below the layer of clouds which is located at a level with $p \sim 0.3$ – 1 bar.

The processes of destruction will significantly affect the motion and the thermal state of the comet fragment. These processes will manifest themselves mainly as splitting of the comet material, phase transitions (fragmentation, melting, and vaporization of the comet material), as well as relative displacements of parts of the fragments. Under the action of normal stretching stresses, large pieces of the fragment will split off from its rear and side surfaces.

However, owing to the relatively gradual increase of the gasdynamic loads and their long duration, a reflection of compression waves from the free surfaces is likely to lead to noticeable stretching stresses only in the regions of collapse (i.e. geometrical convergence of load-relieving waves). Estimates show that the compression waves themselves will exert a much more destructive action on the comet fragments. A rapid, virtually adiabatic deformation of the leading front of the fragment will produce a wave of phase (structural) transitions following an elastic forerunner in the solid body. Under relatively low gasdynamic loads, corresponding to the initial stage of the fragment's penetration into the atmosphere of Jupiter, this wave of structural transitions will be a fragmentation wave. Models of this kind were considered in Ref. [23]. As the fragment penetrates deeper inside the atmosphere, gasdynamic loads increase, and melting and vaporization of the comet material will occur in addition to the splintering. The nature of flow past a rubble pile differs only slightly from that past a compact fragment at this stage. If we assume that the destruction of the fragment will begin where the density of the surrounding medium ρ_* is of the order of σ_*/v^2 — where σ_* is the compressive strength of the fragment material — we obtain $\rho_* \cong 2 \times 10^{-6}$ g cm^{-3}, which corresponds to an altitude of ~ 100 km in the Jovian atmosphere.

In addition to direct destruction (melting, vaporization) of the frontal part of the fragment, the fragment undergoes deformation as a whole. This deformation is caused by inhomogeneities of pressure in the shock-compressed layer. Since the pressure is maximum at the centre of the frontal surface of the fragment and drops rapidly toward its edges, such distribution of the load leads to the removal of the fragmented material and to squeezing out of the liquid (or gas-like) phase to the periphery of the frontal part and to its subsequent carrying away by the stream flowing past the body, as well as to plastic spreading of the fragment perpendicular to the direction of its motion, and finally to the breakup of the fragment into separate splinters. It should be noted that the fragmentation process is repeated for each sufficiently large fragment until the aerodynamic loads give rise to stresses exceeding the strength of the comet material. At this stage the flow past the broken-up fragment of the comet can no longer be treated as flow past a single body; the flow past each sufficiently large component of the initial fragment has to be considered separately. In this case the nature of motion of a rubble pile differs from that of a compact object, because a fragmented body undergoes stronger braking. The more effective braking of fine shot in comparison with a bullet under otherwise equal conditions can serve here as an example. Scattering of the fragment causes in turn a sharp increase in the heat flux generated (which is inversely proportional to the radius of curvature of the object) because of the sharp increase of the effective surface of the fragment and the conversion of matter from the condensed to the gaseous state. As a result, a gaseous cloud forms, the temperature, pressure and density of which significantly exceed those of the adjacent unperturbed atmosphere. The cloud begins to expand intensively and continues to descend at an extremely high velocity. Such a rapid process of gasdynamic cloud formation in this initial stage and its subsequent expansion can be regarded as an explosion.

Note, that the mechanism described above qualitatively explains why small meteorites burn out, whereas large ones explode.

As in the earlier stage (before the explosion), a strong shock wave propagates in front of the cloud, approximately one-tenth of its radius ahead of it.

Explosion of the comet will be accompanied by an optical flash generated both by the shock wave and by hot products of the explosion. The temperature of the shock-compressed layer can reach 2–3 eV at the entry velocity of about 60 km s^{-1} [24].

The energy of the optical radiation can be estimated to be of the order of magnitude of 0.1% of the explosion energy [21]. For a fragment 1 km in diameter we can estimate the power of the flash to be $\sim 10^{26}$ erg s^{-1} assuming a braking time $\tau \sim 1$ s. Note that the flux of solar radiation received by Jupiter is $J \sim 8 \times 10^{24}$ erg s^{-1}, half of it being reflected (the albedo of Jupiter in the optical band is ~ 0.5). Therefore, the braking of the comet by Jupiter's atmosphere would be seen as a bright flash even if it occurs on the light side of Jupiter. Since the fragments of comet Shoemaker–Levy will fall onto the dark side of Jupiter, this flash can be seen only when the explosion takes place close to the terminator. In this case we shall see the burst of radiation scattered by the Jovian atmosphere as an auroral light. It must be remembered that the cloud cover of Jupiter will partially screen this radiation.

Another way to see the burst of radiation is to try to observe the reflected flash on one of the appropriately situated Jovian satellites. The satellite will then act as a mirror reflecting information on the comet's explosion to the Earth.

In this case the flux of solar radiation reflected from the satellite should be compared with the reflected radiation of the flash produced by the explosion of the comet. For the best known Jovian satellite, Io, the flux of the reflected solar radiation is $J_s \sim 2.5 \times 10^{21}$ erg s^{-1} (Io's albedo was taken as 0.5), whereas the reflected flux of the burst of radiation is $J_e \sim 2 \times 10^{19}$ erg s^{-1}, i.e. $J_e/J_s \approx 8 \times 10^{-3}$; therefore, the bursts of radiation accompanying the demise of large fragments of comet Shoemaker–Levy are quite observable as long as they are not screened by cloud cover. Note that the ratio J_e/J_s will be one order of magnitude higher for the satellite nearest to Jupiter, Methys (although the absolute values of the fluxes will be significantly lower because this satellite is only 10 km in radius).

Below we give some results of numerical simulation of gasdynamic processes arising after the explosion of one of the comet's fragments entering the Jovian atmosphere with an initial velocity of 60 km s^{-1} normal to the planet's surface. It was assumed that a spherical fragment 1 km in radius with an initial density $\rho_i = 1$ g cm^{-3} explodes at a height $h_s = -150$ km ($p_s \approx 30$ bar, $\rho_s \approx 1.8 \times 10^{-3}$ g cm^{-3}).

Numerical calculations show that this assumption is not crucial for estimating long-term atmospheric consequences because of small variations of the kinetic energy of the fragment in the upper atmosphere.

The velocity of the fragment just before the explosion was assumed to be 50 km s^{-1}; the gas pressure in the cloud just after the explosion, p_0, was assumed to be equal to the stagnation pressure in the direction of the drag ($p_0 \approx \rho_s v^2$).

Cylindrical coordinates (r, z), with the z axis pointing in the direction opposite to the gravity force vector, were used in the calculations.

The pattern of gasdynamic flows taking place after the comet's explosion is characterized by the following main features.

Soon (tenths of a second) after the explosion the bulk of the fragment material is concentrated in a cup-shaped layer ~ 3 km in radius, about 1 km thick, with the rim of the cup directed upward. This shape may be explained by the strong drag that the front of the cloud experiences on entry into the dense layers of the atmosphere, while the main part of

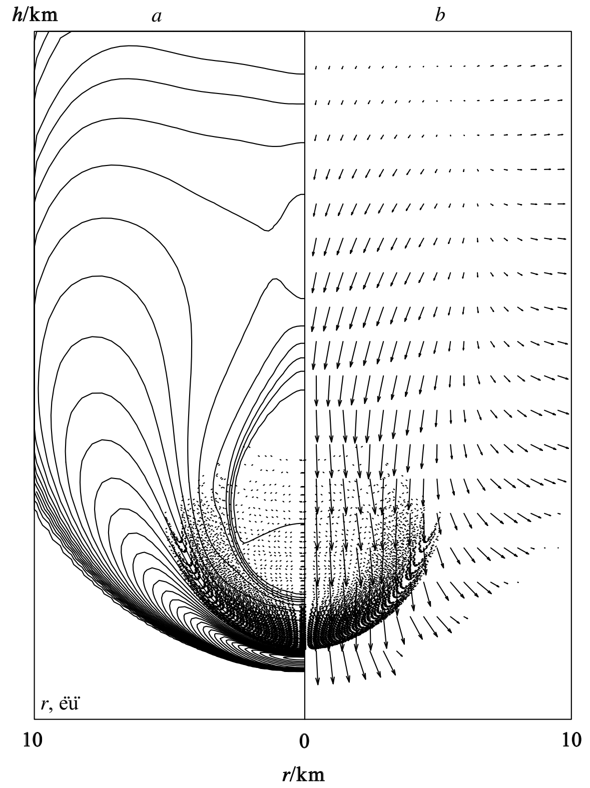

Figure 5 Isotherms (a) and the velocity field (b) 0.6 s after the explosion of the comet at a height $h = -150$ km (atmospheric pressure $p \approx 31$ bar). Particles of the comet's fragment are marked with dots. Maximum flow velocity is $v_{\max} = 42$ km s^{-1}.

the comet continues its inertial motion with a velocity exceeding that of the front of the cloud. Isotherms 0.6 s after the explosion are presented in Fig. 5a and the corresponding velocity field is shown in Fig. 5b. A temperature maximum corresponding to nearly 22 000 K is located in the shock layer between the forward shock wave and the moving cloud. The maximal velocity in the gasdynamic flow is $v_{\max} = 42$ km s^{-1}. At this moment a portion of the gas at the cloud periphery has already started to move upward, while the main part of the cloud continues its downward motion. Isotherms reveal a local maximum, increasing with time, in the tail of the cloud. Immediately behind the cloud a region of rarefied gas is formed, into which streams the Jovian atmosphere. Gas streaming into the rarefied region decelerates in the vicinity of the axis in the tail part of the cloud, resulting subsequently in the generation of a local density jump.

At time $t \approx 1$ s the gaseous cloud formed from the comet material increases significantly in size (to $R \approx 7$ km), actively interacting with the Jovian atmosphere through which it moves (Fig. 6). This moment is characterized by the formation of a floating density jump in the tail of the cloud, as well as by increased drag experienced by the frontal part of the cloud due to the increase of its effective cross section. The velocity maximum becomes displaced to the tail of the meteorite cloud. The maximal velocity in the stream is now $v_{\max} = 38$ km s^{-1}. A strong vortex with a centre 5 km away from the axis of symmetry is formed at this time. From then onwards a significant part of the fragment material and of the adjacent atmosphere is captured by the region of the vortex flow. Constant radial velocity lines corresponding to the instant $t \approx 1$ s are presented in Fig. 6. The departure of the shock wave

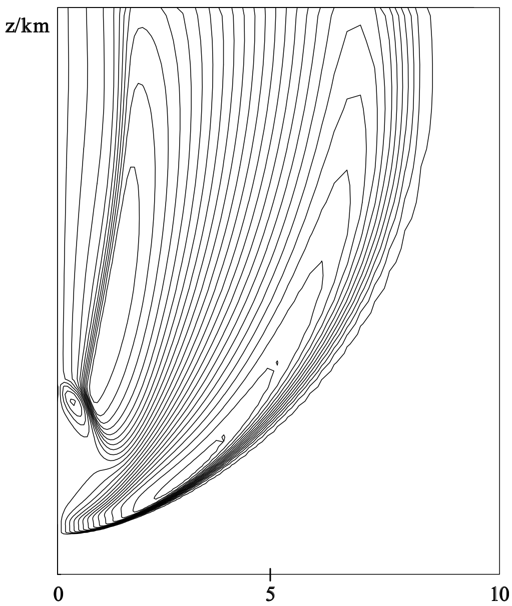

Figure 6. Lines of constant radial velocity component of the flow 1 s after the explosion

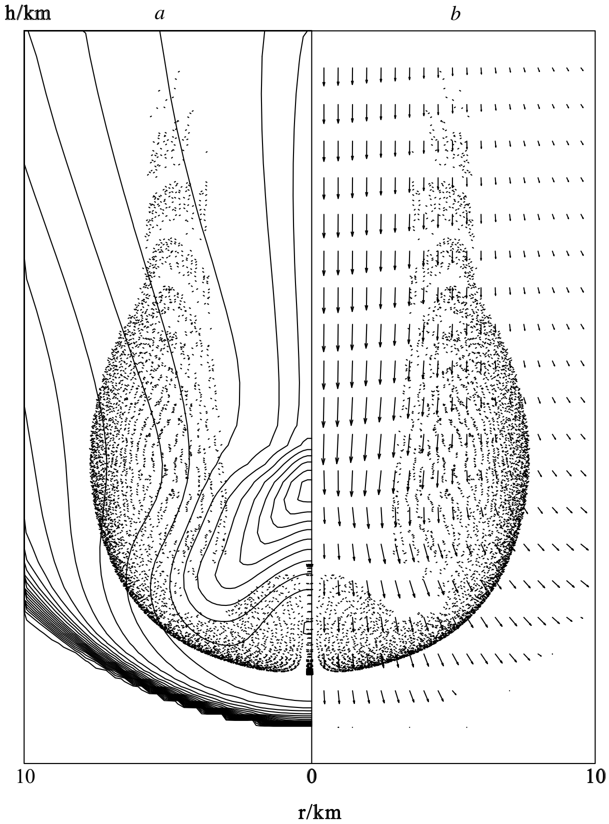

Figure 7. Isotherms (a) and the velocity field (b) 4 s after the explosion of the comet. Particles of the comet's fragment are marked with dots. Maximum flow velocity is $v_{\max} = 19$ km s^{-1}.

away from the axis of symmetry is clearly seen in the tail of the cloud.

Isotherms and the velocity field at time $t = 4$ s are shown in Figs 7a and 7b, respectively. The cloud now undergoes significant deceleration, so that the maximum velocity of the flow is reduced to 19 km s^{-1}. The most intensive gas motion occurs in the tail of the cloud, with particles of cometary material at the perimeter of this cloud forming a characteristic pear-like shape. The radius of the cloud is 7 – 8 km. Some comet material remains in the stagnation zone at the front of the cloud, while the main part is captured by the vortex. A plume of cometary material follows the cloud at a distance of 4 – 6 km from the axis.

At time $t \approx 6$ s after the explosion (Fig. 8) the front side of the cloud comes almost to a standstill, moving with a velocity about 1 km s^{-1}, while the gas in the tail continues to move intensively downward with a maximal flow velocity up to 8 km s^{-1}. The cloud radius is now equal to 10 km. The formation of a vortex ring is clearly seen in Fig. 8. The bulk of the cloud material is drawn into the toroidal core of the vortex. The core moves down with a velocity of 4 km s^{-1}. At the same time, gas at the periphery of the cloud moves upward with a velocity of 1 km s^{-1}. The comet cloud reaches its maximum height $h_{\min} \approx -240$ km which corresponds to a pressure of $p_{\max} \approx 100$ bar. By then, the frontal shock wave has become much weaker, has spread, and moved away from the cloud some 3 – 4 km. The shock wave then continues to move downward and rapidly decays. The global maximum of temperature moves from the shock wave to the cloud centre. The cloud temperature reaches 4000 K (by now the cloud consists primarily of atmospheric gas). This moment is characterized by the formation of a thermal (a cloud of heated gas in a convective weakly perturbed atmosphere).

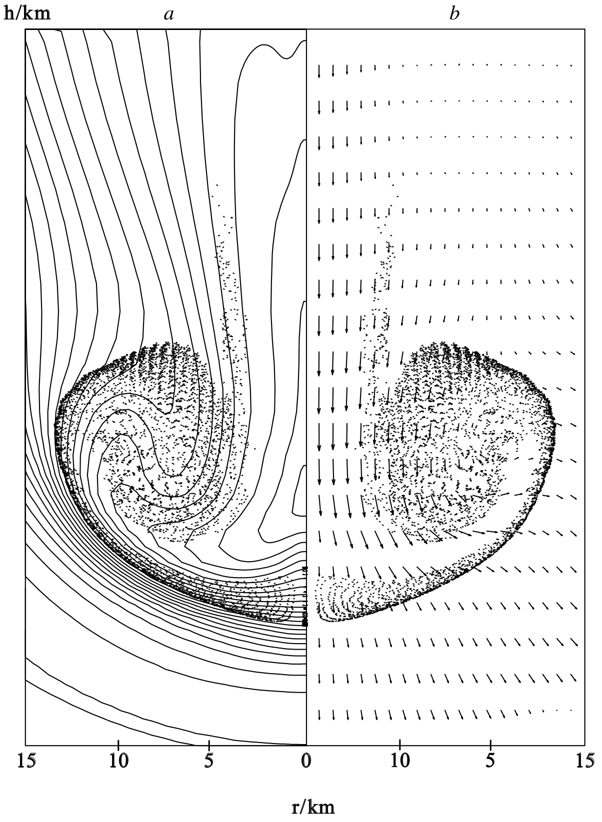

Figure 8. Isotherms (a) and the velocity field (b) 6 s after the explosion of the comet (the moment at which the cloud has stopped moving downward and has penetrated to the lowest altitude in the Jovian atmosphere). Position of the front of the cloud corresponds to a height $h = -240$ km and to a pressure $p = 100$ bar.

At the next stage the comet cloud floats upward under the action of the Archimedean buoyancy force. The pattern of the gasdynamic flow becomes complex with a clearly defined stream flow. In the late stage of the floating of the gaseous cloud upward, turbulent mixing becomes significant.

In calculations of the upward motion of the thermal, the atmosphere above the height of the explosion h_s was assumed to be unperturbed, and the influence of the trail of the fragment was not accounted for. In this way the long-term consequences of the inclined entry of the fragment into the Jovian atmosphere are simulated; the cloud will then float upwards under the action of the buoyancy force in an unperturbed gas.

As the thermals float upward, two qualitatively different patterns of flow are usually observed. In one case the gas swirls, forming a large, rising eddy ring, and in another case a stream directed upward is formed. Which scenario prevails depends on different factors, but primarily on the altitude at which the thermal is formed. Note, that in Earth's atmosphere the boundary separating these two possible flow patterns corresponds approximately to a height of 40 km. Fig. 9 shows the velocity fields, isotherms, and comet particle distribution at time $t = 40$ s. At this stage one can observe a clearly defined upward flow entraining further atmospheric masses. The maximum velocity of the gas rising is 3.5 km s^{-1}. Note that the bulk of the comet material is concentrated not at the axis, but in the vortex 5 – 15 km away from the axis. The height at which the comet material with its plume is distributed ranges from -180 km to -130 km. The column of rising gas is about 40 km in diameter and contains of only 10% – 15% of the comet material. As the thermal rises the comet material becomes compressed, because the bottom layers rise at a greater velocity than the top ones.

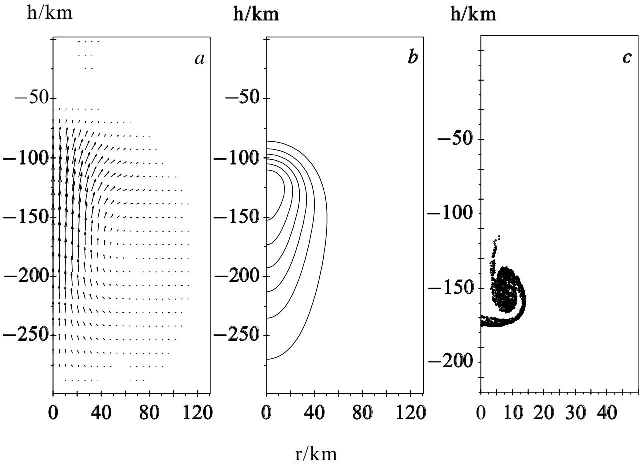

Figure 9. The velocity field (a) and isotherms (b) (the isotherms are spaced 150 K apart); (c) markers corresponding to the location of the comet material 40 s after the explosion.

After 1.5 min, the gas stream still continues to be rise. The shape of the comet cloud gradually changes its topology to a 'disc' 30 km in radius. The maximum gas velocity reaches 4 km s^{-1}.

The upward motion of the gas slows down with time, and at a later stage (close to the moment when the cloud becomes suspended) turbulent mixing begins to influence more and more the process of cloud formation; this has been taken into account in our calculations with the use of the $k-\varepsilon$ model [25].

Some 6 min after the explosion, a cloud containing the explosion products forms, which occupies a region up to 100 km in horizontal radius and 50 km in height. This cloud rises to a height of 250 km, which is significantly higher than the formation level of natural Jovian clouds. The maximum temperature in the rising gas stream is about 700 K. Although its maximum upward velocity is 500 m s^{-1}, the cloud almost stops rising, and appears suspended.

Fig. 10 shows the situation 10 min after the explosion. The gaseous cloud has almost stopped rising. Temperature of the gas does not exceed 500 K. At this stage the cloud containing the comet products is spreading slowly horizontally. The radius of the cloud is 150 km and the average height at which the cloud hangs is 250 km.

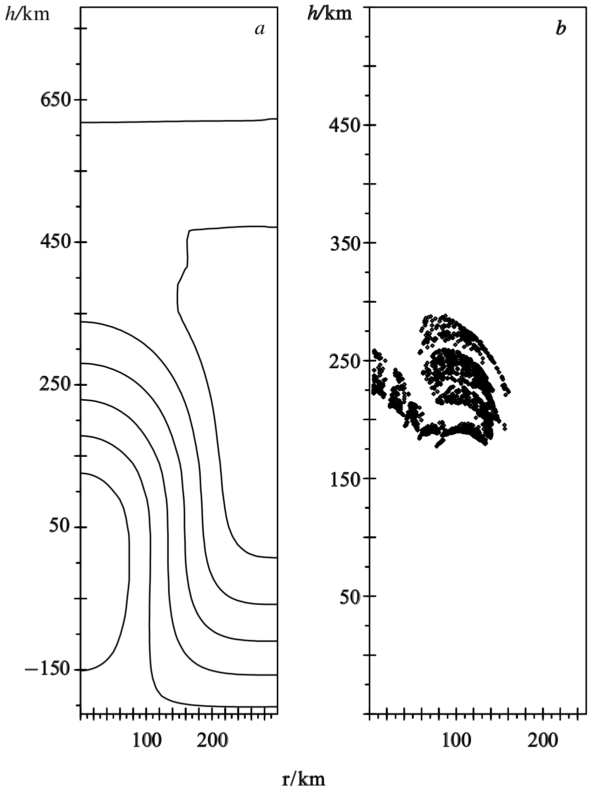

Figure 10. Isotherms (a) spaced 65 K apart; (b) markers, corresponding to the location of the comet material 10 min after the explosion.

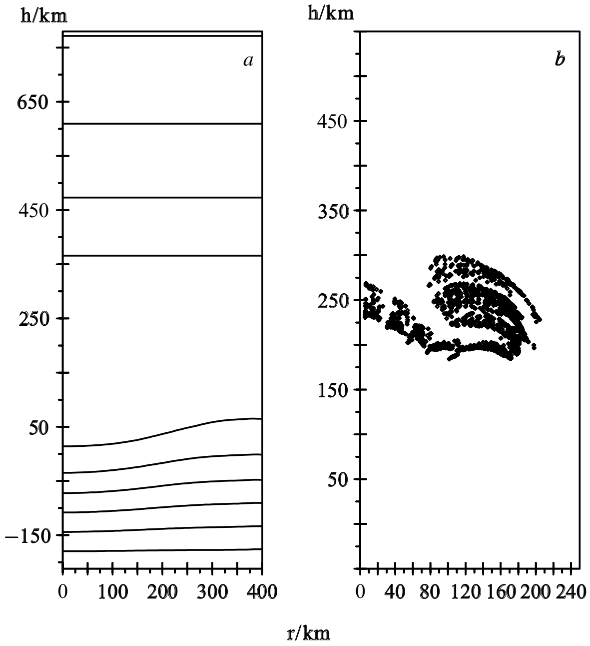

Figure 11. Isotherms (a), and markers corresponding to the location of the comet material (b).

Calculations shows that 1 h after the explosion (Fig. 11) the parameters of the gaseous cloud approach those of the surrounding medium (for example, to within a few tens of degrees in temperature). These changes are caused by the continued slow spreading of the cloud comprising the comet material. The cloud radius has now reached 200 km. Its thickness practically does not increase, because the turbulent mixing energy in the vertical direction is expended mostly on action against the gravity force. Later on, the cloud may spread over several thousand kilometres. Note that the calculations were performed for an unperturbed atmosphere (i.e. without wind). Intensive convective currents in the Jovian atmosphere can significantly alter the picture described above.

Thus, braking and explosion of the comet fragment in the Jovian atmosphere lead to the formation of a cloud and to its propulsion by the Archimedean force to a mesospheric height of $h \approx 250$ km ($p_h \approx 1.6 \times 10^{-5}$ bar) at which it comes to rest. A few hours after the explosion, when Jupiter's rotation will make the site of interaction of the fragment with the atmosphere observable from Earth, the cloud of explosion will have the form of a disc with a diameter D_f of the order of one thousand kilometres and a thickness h_f of the order of one hundred kilometres.

The density of the comet material in the cloud ρ_c can be easily estimated: $\rho_\mathrm{c} \sim \rho_i D^3 / D_\mathrm{f}^2 h_\mathrm{f} \sim 10^{-9}$ g cm^{-3}. Note that when the cloud is no longer moving, it is composed of nine parts Jovian air and one part comet matter, that is the cloud retains information about the explosion. This is a specific 'memory' of the preceding collision, and our calculation shows that the Jovian atmosphere will 'remember' comet Shoemaker–Levy, or, more precisely, each of its rather large fragments, for a minimum of several hours after the explosion. We can 'see' this cloud because of the characteristic fluorescence of the comet material. This question will be discussed in the next section.

The fate of the cloud formed by the explosion of a rather large comet fragment with a size of $D_i \approx 1$ km was outlined above with the use of numerical modelling. Now we turn to the question, to what extent these results are applicable to the description of the behaviour of the clouds formed by the explosion of the smaller comet fragments (with typical sizes of $D_i \sim 100$ m).

The velocity $v_{\rm cl}$ at which the heated cloud rises can be determined from:

$$v_{\rm cl} \approx (gD_{\rm cl})^{1/2}\,, \tag{5}$$

where $D_{\rm cl}$ is the cloud size, and g is the gravitational acceleration ($g \approx 25$ m s^{-2} for Jupiter). For the initial size of the cloud one easily obtains:

$$D_{\rm cl} \sim \left(\frac{E}{p_{\rm s}}\right)^{1/3} \propto \frac{D_i}{p_{\rm s}^{1/3}}\,, \tag{6}$$

where E is the energy of the explosion.

Taking into account that the pressure of the surrounding atmosphere at the level of explosion $p_{\rm s} \propto D_i$, we find that the upward velocity of the cloud $v_{\rm d} \propto D_i^{1/3}$, that is it depends weakly on the initial size of the fragment.

The height difference the cloud formed by the explosion overcomes is $\Delta h_{\rm cl} \approx v_{\rm cl}^2/2g \sim D_i^{2/3}$. Note that the large comet fragments penetrate deeper into the Jovian atmosphere than the smaller ones, so that the heights at which the braking of the fragments of both sizes takes place will not differ too much for the fragment sizes $D_i \sim 0.1-1$ km.

Therefore all twenty fragments of comet Shoemaker–Levy will eventually be observed in the Jovian atmosphere at heights of ~ 200 km. The heights of suspension of the clouds derived from different fragments of the comet will not differ much from each other, although some differentiation of the fragments by height will take place. Most important for us is the fact that these clouds will be well above the cloud cover and will be observable.

The question arises whether the weak glow of the comet material in the upper Jovian atmosphere under the effect of solar radiation is all that will be observed from such a powerful explosion. If zonal atmospheric currents tear apart the cloud of explosion, it will be difficult to record even this radiation.

A mechanism exists — described qualitatively below — which in our opinion is able to 'reveal' some special features of large fragments the comet Shoemaker–Levy plunging into the Jovian atmosphere. Specifically, we refer here to internal gravity waves. These waves can be represented as vertical displacements of atmospheric layers by the action of gravity. On Earth, internal gravity waves are effectively excited by, for example, forest fires. Note that in hydrodynamics such waves are called buoyancy waves. In other words, the atmosphere 'breathes' when an internal gravity wave is excited.

Internal gravity waves with a wavelength equal or greater than the cloud size, $\lambda \geqslant D_{\rm cl}$, are effectively generated when a fragment of the comet explodes in the Jovian atmosphere and the cloud of explosion floats upward. Now, imagine that during the process of the vertical transport induced by the wave, a layer of atmosphere penetrates into a region with a substantially lower temperature. If condensation is possible, then a characteristic cloud cover will be formed. We believe its formation is stimulated by the transit of the internal gravity wave generated by the cloud of explosion. In the Jovian troposphere ($p \sim 1-0.1$ bar), the temperature decreases with increasing height. Atmospheric scale (height scale) is $H \sim 25$ km at the tropospheric level. The velocity of propagation of an internal gravity wave $v_{\rm w}$ can be estimated from the relation $v_{\rm w} \approx \lambda N/2\pi$, where N is the Brunt– Vaisala frequency,

$$N^2 \approx (\gamma - 1)\frac{g^2}{c_{\rm a}^2}\,, \tag{7}$$

where γ is the adiabatic exponent and $c_{\rm a}$ is the speed of sound. In the Jovian troposphere $v_{\rm w} \sim 200$ m s^{-1}.

Large fragments of comet Shoemaker–Levy will explode significantly below the tropospheric heights. However, when a fragment passes the troposphere before the explosion, the wavelength of the excited wave (as well as its amplitude) is of the order of the size of the fragment, ~ 1 km. Since the decay γ of these waves is inversely proportional to the square of the exited wavelengths ($\gamma \propto \lambda^{-2}$), such shortwave perturbances can safely be neglected.

It is natural to assume that gravity waves are excited more effectively when the cloud of explosion (at these heights its size is about 70 km) rises through the troposphere, than when the the comet fragment passes downward through the same heights before the explosion.

The results of numerical modelling reveal a significant enlargement of the cloud of explosion as it crosses the troposphere, $D_{\rm cl} \sim 70$ km, with the gas inside the cloud being heated to temperatures ~ 1000 K. At these heights the amplitude of the wave $\sim D_{\rm cl} \geqslant H \approx 25$ km, so there is a high probability that condensation and stimulated formation of clouds in the Jovian troposphere will occur.

Therefore, a 'wave of abnormal cloudiness' will be excited in the troposphere. In $\tau \sim 5$ h (the time when this will be observable) this wave, propagating from the epicentre with a velocity $v_{\rm w} \sim 200$ m s^{-1}, will expand to a size $\sim v_{\rm w}\tau \sim 5000$ km (i.e. as large as the Great Red Spot). Note that decay of the internal gravity wave can be neglected on such time scales.

In reality this picture will be much more complicated, especially if one takes into account that a siginificant natural cloud cover reducing this effect is present in the troposphere.

On the other hand, the hot cloud of explosion passing through the layer of natural clouds (located at heights $h \sim 0-40$ km) as it crosses the troposphere will 'burn out' a hole with a diameter $\sim D_{\rm cl} \approx 70$ km in the cloud cover, so that five hours later the site of the entry of the fragment into the atmosphere may be discovered (providing, of course, the site is not screened by clouds). Such an effect will be absent if the comet explodes above the troposphere.

Therefore, by observing variations in the cloud cover in the troposphere, we can get information both about the properties of the Jovian troposphere and about the drag to which large fragments of comet Shoemaker–Levy are exposed, and obtain more precise coordinates of the sites where the fragments enter the Jovian atmosphere.

5. Perturbations in the upper atmosphere and the magnetosphere of Jupiter

The atmosphere of Jupiter at the heights where the cloud of explosion decelerates consists primarily of molecular hydrogen (the amount of helium is about 10%). We can 'see' the cloud of explosion by the specific glow of the comet material, excited by solar radiation. Two processes make the cloud observable: resonance scattering, when a photon is absorbed by atoms and molecules and is reradiated with the same energy, and fluorescence, when the energy of the emitted photon is less than that of the absorbed photon.

An hour after the explosion, the cloud consists of $\sim$90% of Jovian atmosphere and $\sim$10% of the comet material. Parameters of the surrounding atmosphere are: $\rho \sim 10^{-8}$ g cm^{-3}, $p \sim 6 \times 10^{-5}$ bar; density of the comet material in the cloud is $\sim 10^{-9}$ g cm^{-3}.

We shall assume the comet to consist of ice, so that the main radiation of the cloud stems from molecules of water and oxygen, and also possibly from products of their reactions. Consider the contribution of molecules of water, oxygen, and hydroxyl to the radiation. Radiation of metals, which may constitute a certain part of the comet material, will be considered separately.

As the side of Jupiter where the collision took place turns towards to the Sun, regions of the atmosphere containing the comet material will begin to fluoresce under the action of the solar radiation and thus will differ in their spectral characteristics from the surrounding natural atmosphere of Jupiter, which at these heights is practically deprived of molecules of water and oxygen.

It is important to note that we do not attempt to describe in detail the radiative spectrum of the cloud, but simply stress the fact that the cloud will fluoresce under the action of incoming solar radiation, and that it should be possible to detect this fluorescence (and resonance scattering).

In the dense atmospheric layers of Jupiter (in the troposphere) molecules of water and oxygen are surely present, but in these layers they are under a pressure of about 1 bar, and an effective collisional quenching of the excited molecules prevents radiation. Rayleigh scattering of the incoming solar radiation without photon absorption is much more effective at these altitudes.

For the radiation on transition from the jth excited state to be seen, it is necessary that the inequality $A_j \geqslant \nu \propto \rho$ be fulfilled, where A_j^{-1} is the lifetime of the jth excited state, and ν is the collisional frequency of the excited atoms and molecules leading to the quenching of the excitation.

According to numerical calculations, the cloud of explosion containing molecules of water and oxygen is decelerated at altitudes where quenching of the aforementioned radiations is ineffective. To begin with, consider radiation of metastable components of the comet cloud. Visible radiation of the cloud of explosion is determined primarily by the oxygen atom: the emission O(^{1}S) at a wavelength 5577 Å is generated by the O(^{1}D—^{1}S) transition. This emission corresponds to the so-called 'green line', which can be visually observed in the polar glow on Earth. The lifetime of the O(^{1}S) state with respect to radiative decay is about 1 s.

Let us estimate the radiative flux I_j generated by the cloud of explosion of one of the fragments, which one can try to detect on Earth:

$$I_j = \frac{n_j}{4\pi R_{\mathrm{je}}^2} A_j V \, . \tag{8}$$

Here V is the volume of the emitter (the emitter is a cloud of plasma assumed to be optically thin); n_j, A_j^{-1} are the concentration of the atom or the molecule in the jth state and its lifetime, respectively; R_{je} is the distance from Jupiter to Earth ($\sim 6 \times 10^8$ km). To estimate the flux I_{5577} at the wavelength 5577 Å, one needs to know n_{5577}; its order of magnitude can be determined by means of the values of n_{5577} observed in the terrestrial atmosphere at altitudes of $h \sim 85-100$ km. Such an analogy seems to be acceptable for a rough numerical estimation of the I_{5577} flux, as concentrations of the atomic oxygen in the cloud of explosion in Jupiter and in the terrestrial atmosphere at these heights are of the same order. One should also take into account the attenuation of the solar radiation reaching Jupiter by a factor of 25 relative to Earth. This yields for the I_{5577} radiative flux the value of $\sim 10^{-3}$ cm^{-2} s^{-1}.

This means that about three 'green' photons fall every hour onto a unit area of the Earth's surface (1 cm^2). We note that by daytime the radiative flux at the wavelength 5577 Å $I_{5577} \sim 10^9$ cm^{-2} s^{-1}, that is twelve orders of magnitude more intense. This radiation is generated in Earth's atmosphere at heights of about 90–100 km, through the photodissociation of molecular oxygen by solar radiation. At night time the intensity of I_{5577} is an order of magnitude lower, and the formation of O(^{1}S) occurs at heights as low as ~ 250 km as a result of dissociative recombination of the O_2^+ ion. It is extremely difficult to detect three photons from Jupiter (and this is, moreover, the upper limit) against such a background†.

Thus, to observe the cloud of explosion one needs either to look for emission lines and bands that are not present in the atmosphere of Earth but are present in the cloud of explosion (such lines are most probably absent for a comet composed primarily of ice), or to try to record the emission of the cloud of explosion by using space apparatus orbiting at heights where the background emission of the terrestrial ionospheres in the observed lines and bands is strongly weakened.

Such radiation, in our opinion, can be generated by hydroxyl, because its concentration is insignificant at great altitudes in the atmosphere of the Earth. Specifically, we mention the 3090 Å band of the system OH($\mathrm{A}^2\Sigma^+ - \mathrm{X}^2$). The concentration of hydroxyl in the cloud of explosion can be quite high and reach $\sim 10^{12}$ cm^{-3}. The bulk emissivity is $i_j = A_j n_j = n g_j$, where n_j is the hydroxyl concentration, g_j is the so-called emissivity factor, which accounts for excitation of the 3090 Å band by the solar radiation. For the Jovian hydroxyl the emissivity factor g_j of the 3090 Å band is around 5×10^{-5} s^{-1} [27]. This yields a value for the radiation flux I_{3090} at the wavelength 3090 Å reaching the Earth of $\sim 10^2$ cm^{-2} s^{-1}, that is five orders of magnitude greater than at the wavelength 5577 Å.

These figures give reason for cautious optimism, especially if there will be an opportunity to carry out measurements at heights where the hydroxyl background radiation is practically absent (for the ionosphere of Earth this corresponds to heights $h \geqslant 150$ km).

Observations of resonance scattering and fluorescence are most effective for permitted transitions, since the lifetime of the excited state for such transitions is extremely short. For the majority of chemical elements, the photon energy required for excitation of these transitions falls into the vacuum ultraviolet band where the solar radiation intensity rapidly decreases, so that the emissivity factors for such transitions are small. The situation is radically different for excitations of lines of metals having low-energy resonant transitions. This is applies primarily to metals with lines excited by optical radiation, such as sodium (5890 Å line), lithium (6708 Å line), and potassium (7699 Å line). The emissivity factors of these transitions can be very high, so that even if the concentrations of these atoms in the

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†Some investigators have studied even finer effects that could accompany the demise of comet Shoemaker–Levy [27].

comet material are low, the lines in question can have large intensities. For example, if the sodium content in comet Shoemaker–Levy is about 0.1%, the intensity of the 5890 Å line on Earth is $\sim 10^4$ cm^{-2} s^{-1} and can be readily detected by ground-based optical facilities. The probability that there are metals in the comet material is quite high, so that corresponding lines may be present in the spectrum of the cloud created by the explosion.

Should the explosion give rise to ejection of material (both cometary and entrained atmospheric gas) into the mesosphere and thermosphere of Jupiter (when the fragment is more than about 1 km across), then when the resulting jet is ionized even to a small extent, its motion inside the magnetic field of Jupiter will generate low-frequency radiation which could lead to observable perturbations of the magnetosphere, in particular to variations in radioemission from the inner radiation belts.

The magnetic field of Jupiter can be described to our required accuracy in the dipole approximation, with the dipole axis being coincident with the rotational axis. Then it is readily found that the equatorial point of the magnetic field force line crossing the surface of Jupiter at a latitude λ is located at a distance r_0 from the centre of Jupiter,

$$r_0 = \frac{R_{\mathrm{J}}}{\cos^2 \lambda} \,, \tag{9}$$

where the radius of Jupiter $R_{\mathrm{J}} \approx 70\,000$ km.

For the force line at the latitude of the explosion ($\lambda \approx 45^\circ$ S), $r_0 \approx 2R_{\mathrm{J}}$. The magnetosphere region $1.3R_{\mathrm{J}} \leqslant r_0 \leqslant 3R_{\mathrm{J}}$ is the source of nonthermal decimetre electromagnetic radiation ($f \geqslant 300$ MHz) [16]. This high-frequency radiation is due to synchrotron emission of relativistic electrons captured by the planet's magnetic field. Typical energies of the relativistic electrons generating this radioemission are of the order 10–20 MeV. Electrons with such energies move along the force lines of the magnetic field of Jupiter by oscillating between mirror points with a bounce period τ_{b} of the order of one second. Since the mirror ratio for the force tube passing through the point of explosion is ~ 16, a portion of the fast electrons from the loss-cone will spill out from the magnetic trap and be lost in the upper atmosphere of Jupiter.

Sporadic bursts of intensity of the decimetre radioemission from the inner radiation belts of Jupiter are hardly ever observed. Hence, one usually assumes the inner radiation belts to be stable: the outflow of fast particles through the sides of the magnetic trap is compensated by relativistic electrons captured by the trap as a result of radial diffusion from regions with lower magnetic field.

Low-frequency magnetohydrodynamic waves (for example, Alfven waves), which we believe will be generated inside the force tube passing through the point of explosion, have characteristic frequencies commensurate with τ_{b}^{-1}, so one would expect the spilling out of the relativistic electrons to be modulated with the frequency of the Alfven waves. The intensity of emission of relativistic electrons in this magnetic force tube will therefore be modulated with the same frequency. This is a rather fine effect, but we do hope that it can be detected by ground-based radiophysical facilities.

6. Conclusions

We considered here, largely at the quantitative level, the explosion of comet Shoemaker–Levy 9 in the atmosphere of Jupiter. The high altitudes at which the clouds of explosion will end up suspended in the atmosphere of Jupiter should provide opportunities for them to be observed. One can expect significant changes in the structure of the cloud layer of Jupiter at tropospheric heights; in particular, we believe it will be possible to observe a stimulated 'wave' of anomalous cloudiness in the troposphere. It should be possible to observe the fluorescence of the cloud of explosion from space-based observatories. Variations of the decimetre radiation flux in the force tube of magnetic field passing through the point of explosion of the comet are possible. However, it is clear that the real picture of the collision of comet Shoemaker–Levy with Jupiter will prove to be much more prolific than that provided by current theoretical predictions, and observational data that will shortly be acquired will transform our understanding of the nature of the interaction of large comets with the atmospheres of planets.

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