# Collision of a comet with Jupiter: Light curve fine structure

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The results of Earth-based infrared observations of Jupiter during the collision with comet Shoemaker–Levy 9 fragments are analyzed. The impact of a typical comet fragment produces three peaks in the light curve. The first two flashes are short-lived and weak while the third flash is very bright and long-lived ($\simeq$20 min). It is shown that the widely accepted explanation of the main peak as thermal radiation from the atmosphere heated by the gas ejected upwards by the explosion of the fragment and falling back down is unsatisfactory. A model is proposed for the physical processes which produce the radiation during the collision with the comet. The shape of the light curve and the origin of the three flashes are explained on the basis of this model. 

The collision of comet Shoemaker–Levy 9 (SL9) with Jupiter occurred in July 1994. The collision process was observed on Earth and by the Hubble telescope and the Galileo spacecraft. In our preceding work[1] we discussed the results of the optical observations performed by the Galileo spacecraft[2] with whose aid the collision process was directly observed. An explanation of these results was proposed.

The explosive character of the energy release as a comet fragment decelerates in the atmosphere results in the formation of a strong shock wave (SW) which in turn forms a region of hot, strongly ionized, optically dense plasma (often termed a fireball (FB)). The fireball cools by means of radiation, which results in the formation of a radiative-cooling wave traveling toward the center of the fireball with velocity $u \propto p_e^{-1}$, where $p_e$ is the atmospheric pressure at the altitude of the explosion (for example, $p_e \simeq$ 10 bar for a kilometer-size fragment). Therefore the radiative-cooling wave decreases the area of the fireball. The duration of the fireball radiation can be estimated by dividing the initial radius of the fireball by the velocity $u$ of the cooling wave. This gives $\approx$40 s for the explosion of a 1-km fragment. This radiation was recorded by Galileo. In Ref. 1 a quantitative description, agreeing well with the Galileo data, was proposed for the duration of the flash and the intensity of the radiation from the fireball formed by the explosion of the comet fragments.

It should be noted that the explanation of the radiation flash registered by Galileo as the radiation from a meteor wake (hot channel formed in the atmosphere as the comet fragment decelerates) lying above the cloud layer (the radiation is strongly screened below the cloud layer) is unsatisfactory. If the meteor wake is optically dense, then it cools by means of radiation, just as the fireball. In this case, however, the velocity $u_w$ of the radiative-cooling wave in the wake ($u \propto 1/p$) is much higher than in the fireball: $p_w \ll p_e, u_w \gg u_e$, where $p_w$ is the pressure in the wake. For this reason, the duration of the flash from an optically dense meteor wake above the cloud layer ($p_w \leq 0.3$ bar) does not exceed several seconds. We note that the radiation intensity is proportional to the energy released as the comet fragment decelerates. In our case the energy released in this process decays exponentially with increasing altitude, and for this reason most of the radiation observed on Galileo during the collision is produced in the fireball. The radiation registered by Galileo is actually the total radiation from the hot, optically dense gas in the fireball and from the meteor wake. But there is a fundamental difference between these two sources of radiation: The flash due to the emission from the meteor wake lasts for a much shorter period of time than the fireball flash, and the flashes can be separated in time by several seconds. Apparently, this scenario was registered by the solid-state radiation detector on Galileo[4] in the case of the impact of fragment $K$.

In Ref. 1 we also examined the results of Earth-based observations of the collision of the comet with Jupiter and we proposed an interpretation of the obtained infrared light curves. A typical Earth-based infrared light curve from the impact of a SL9 fragment contains three peaks. The first two peaks (so-called precursor flashes Pc1 and Pc2) are weak and short-lived, while the third flash, corresponding to the main peak, is bright and long-lived. In Ref. 1 only the main peak was considered in the interpretation of the Earth-based observations. Our objective in the present paper is to examine in detail the fine structure of the light curve. This makes it possible to determine the dominant physical processes which are responsible for the radiation produced during the impact of the comet fragments.

In the present paper the model proposed in Ref. 1 is elaborated and the results obtained on the basis of the model are compared with observational results. Earth-based infrared light curves obtained during the impact of SL9 fragments are analyzed and a qualitative and quantitative model explaining the origin of all three flashes is proposed.

Figure 1 displays the light curve for fragment $R$ at the wavelength $\lambda = 2.3$ $\mu$m.[5] The first peak (precursor Pc1) coincides well in time with the radiation flash registered by Galileo.[6] Apparently, in the case of the impact of fragment $R$ the precursor Pc1 is caused by radiation from the fireball. Since the explosion itself most likely occurred below the cloud layer, only the small fraction of the fireball radiation that escaped through the region of the cloud layer destroyed by the explosion and was scattered by the atmosphere could be observed. This is why the intensity of the flash Pc1 is low.

We note that for a number of impacts the precursor Pc1 was observed on Earth earlier than on Galileo, the characteristic delay being $\sim$10–15 s.[7] This delay could have been caused by the fact that the Earth-based observations registered radiation from the upper atmosphere heated by the dust coma surrounding each comet fragment. This delay can be estimated by dividing the characteristic size of the coma ($\sim$1000 km) by the fragment velocity ($\simeq$60 km/s). However, the Galileo spacecraft did not see this radiation because the intensity of this flash was lower than the threshold of the detectors.[8]

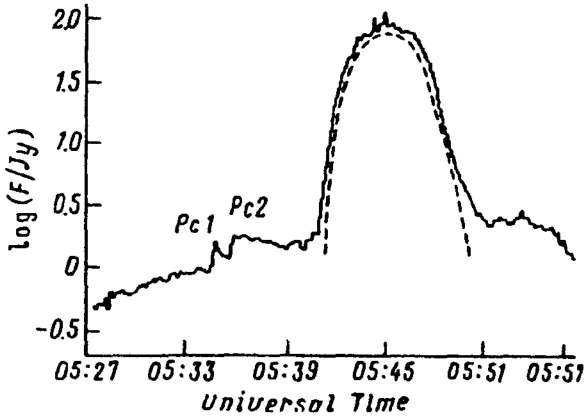


FIG. 1. Light curve for fragment $R$ at the wavelength $\lambda=2.3\ \mu m$.[5] The dashed curve was computed using Eq. (3).

The assumption that the flash Pc1 (and the flashes registered by Galileo) is due to thermal radiation from a meteor wake[9] directly visible from Earth and produced when the comet fragment enters Jupiter's atmosphere cannot explain the observed data. Indeed, the meteor wake from SL9 fragment $R$ is first visible from Earth at an altitude of $\simeq 500$ km above the 1 bar level.[10] The energy released by a decelerating fragment at these altitudes is too low for the observed radiation fluxes (the released energy is $\leqslant 10^{-10}\ E_0$, where $E_0$ is the initial kinetic energy of the fragment). For this reason, the Pc1 flash is most likely of a different origin for different SL9 fragments.

To explain the origin of the second and third flashes, we shall examine the part of the shock wave formed by the explosion of the fragment that propagates upward in the direction of decreasing atmospheric density. At first, the velocity $D$ of the shock wave decreases with increasing distance $R$ from the point of the explosion as $D \propto R^{-3/2} e^{R/2\Delta}$ (Ref. 11) and reaches the minimum value $D_{\rm min}$ at $R \simeq 3\Delta$, where $\Delta$ is the scale height of the atmosphere. As was shown in Ref. 12 (for an explosion at the altitude $h_e \simeq -100$ km, $p_e \simeq 10$ bar, and $E_0 \simeq 10^{29}$ erg), the shock wave starts to accelerate at the $\sim 1$ bar level, and $D_{\rm min} \simeq 5-6$ km/s. At this stage $D \simeq D_{\rm min} e^{(R-3\Delta)/\alpha\Delta}$ (Ref. 13), where $\alpha$ depends on the specific-heat ratio $\gamma$ (for example, $\alpha \simeq 4.9$ for $\gamma = 5/3$ and $\alpha \simeq 6.5$ for $\gamma = 1.2$). The temperature $T$ of the shock-compresssed gas is proportional to $D^2$, and $T_{\rm min} = T_{\rm min}(D_{\rm min}, \gamma) \simeq 2000$ K. When the temperature behind the shock front reaches several thousands of degrees, chemical reactions lead to the formation of molecules such as CO, $CH_4$ $H_2O$, $H_2S$, SH, $NH_3$, and others. As a rule, these compounds dissociate at temperatures of the order of $T_{\rm max} \simeq 4000-5000$ K. We are interested in such compounds because some of these molecules are effective sources of optical thickness of the heated gas. For this reason, the shock-compressed gas can radiate as a black body with maximum spectral intensity at the frequency $\omega_m = 2.82\ kT/\hbar$; the corresponding wavelength, in $\mu$m, is $\lambda_m = 5.08 \cdot 10^3/T$.

We note that the shock-compressed gas starts to expand and cools adiabatically immediately after the passage of the shock wave. The characteristic cooling time after shock compression increases with time, varying from several seconds (immediately after the passage of the shock wave) up to several tens of seconds at a late stage of cooling.[13] As a result, at a late stage (approximately 10 s after the passage of the shock wave) the *minimum* temperature of the shock-heated gas drops to $T \simeq 1000$ K.

As the shock wave accelerates, the temperature of the shock-compressed gas increases as $D^2$ and, as a result, the maximum of the spectral intensity of the radiation shifts into the short-wavelength range. Therefore at the moment the optically dense layer of gas appears its temperature is $\simeq 1000$ K and $\lambda_m \simeq 5$ $\mu$m. As the shock wave accelerates, the temperature reaches the value $T_{\max}$ over the time $t_{\text{Wien}} \simeq \alpha\Delta/2D_{\min} \simeq 15$ s, and $\lambda_m$ decreases to $\simeq 1$ $\mu$m. Then the temperature behind the shock front exceeds $T_{\max}$, and all molecules which are capable of absorbing in the visible and infrared ranges dissociate, as a result of which the gas becomes optically transparent. Therefore the propagation of a strong shock wave upwards through a nonuniform atmosphere gives rise to a layer of heated gas, which radiates as a black body, with an initial temperature ranging from $\simeq 1000$ K to $T_{\max}$.

We now consider the second precursor Pc2 in Fig. 1. In Ref. 10 it was noted that for Pc2 the spectral intensity of the radiation decreases more slowly at short wavelengths $\lambda$, but initially, the longer the wavelength, the higher the intensity is (the observations were performed at the wavelengths $\lambda = 2.3$ $\mu$m, 3.2 $\mu$m, and 4.5 $\mu$m). In accordance with our model, the propagation of the shock wave leads to production of an optically dense layer of gas. At the moment this layer appears, the temperature of the gas in the layer is quite low and its radiation at the wavelengths $\lambda = 2.3$ $\mu$m, 3.2 $\mu$m, and 4.5 $\mu$m is determined by Wien's law ($T \simeq 1000$ K, $\lambda_m \simeq 5$ $\mu$m). For this reason the radiation intensity increases more slowly at shorter wavelengths. As the temperature behind the shock front increases, the spectral intensities at $\lambda = 4.5$ $\mu$m, 3.2 $\mu$m, and 2.3 $\mu$m shift successively into the region of the spectrum described by the Rayleigh–Jeans law ($\hbar\omega \leqslant kT$). This transition occurs by a time $t \simeq t_{\text{Wien}}$ after the optically dense layer appears, and here $T \simeq T_{\max}$, $\lambda_m \simeq 1$ $\mu$m. The subsequent rapid expansion of the shock-compressed gas leads to lower gas temperatures, and the radiating optically dense region becomes smaller. For this region, the spectral intensity of the radiation from the gas during this time interval, while still obeying the Rayleigh–Jeans law, decreases more slowly at shorter wavelengths. As the temperature decreases further, a transition back into the Wien region of the spectrum occurs (first at $\lambda = 2.3$ $\mu$m, then at $\lambda = 3.2$ $\mu$m and $\lambda = 4.5$ $\mu$m) and then the radiation intensity at these wavelengths increases with the wavelength. Therefore the results obtained with the present model are in complete agreement with the data from infrared observations of the second precursor.

It is important to note that in accordance with the proposed model, the second precursor Pc2 can be absent or unnoticeable if the falling comet fragments are large. In this case the minimum temperature behind the shock front can exceed $T_{\max} \simeq 4000-5000$ K, and initially the compressed gas will be optically transparent in this region.

We shall now consider the third peak — the main peak in Fig. 1 — in detail. As long as the temperature of the gas at a late stage of cooling is higher than $T_{\max}$ (the corresponding shock wave velocity $D \geqslant 12$ km/s), all complex chemical compounds are dissociated and the gas is optically transparent. At this stage the upward motion of the gas is almost inertial. By this time the gas layer which was optically dense initially (its temperature immediately after shock compression $T \leq T_{max}$) and which, in our opinion, is responsible for the appearance Pc2, continues to expand rapidly, and the intensity of its radiation decreases. At the same time, the optically transparent gas (heated by the shock wave up to initial temperatures $T \geq T_{max}$) cools. When its temperature drops to $\simeq$2000–3000 K, molecular compounds capable of effectively absorbing infrared radiation start to form in the gas and, as a result, the optical thickness of the gas increases rapidly.

The absorption coefficient $\kappa_\omega$ of the heated gas can be estimated from the formula[14]

$$\kappa_\omega \simeq \frac{2\pi^2 e^2}{mc} \frac{\hbar}{kT} \sum_i f_i N_i e^{-\frac{E_i - \hbar\omega}{kT}}, \tag{1}$$

where $e$ and $m$ are the electron charge and mass, $f_i$ are oscillator strengths, $N_i$ are the densities of molecules that absorb infrared radiation, $\hbar\omega$ is the photon energy, and $E_i$ are the vibrational excitation energies. We note that only vibrational transitions are effectively excited at the temperatures considered. The optical thickness $\tau_{opt}$ of the heated gas can be estimated using the expression (1). Assuming $N_i \geq 10^{16}$ cm$^{-3}$, $E_i \simeq 0.25$ eV, $T_0 \simeq 2000$ K, and $f_i \simeq 10^{-4}$, we obtain

$$\tau_{opt} \simeq \kappa_\omega \Delta \simeq 10^3 - 10^4 \gg 1.$$

Therefore the initial thickness of the optically dense layer is $L_0 \simeq \Delta \ln \tau_{opt} \simeq 10\Delta \sim 250$ km, and the initial transverse size of the layer is $d_0 \simeq 2\pi\Delta \simeq 150$ km.

The further motion of the expanding gas is described by a self-similar solution.[13] According to Ref. 13 , the expansion is initially quasi-one-dimensional, and the concentration varies according to the law $n \propto (t/t_f)^{-1}$, where $t_f$ is the characteristic expansion time at a late stage of cooling (this time depends on the altitude of the explosion: For the layer under consideration $t_f \simeq 20$–30 s (Ref. 12 )). The spatial scale $\Delta_L$ of the layer increases as $\Delta_L \simeq \Delta(t/t_f)$. The decrease in temperature is due solely to adiabatic expansion, which with time becomes three-dimensional: $n \propto t^{-3}, T \propto n^{\gamma-1} \propto t^{-3(\gamma-1)}$. Approximately one minute after it is formed, the optically dense layer of gas reaches altitudes where its radiation can be directly observed from earth. The maximum altitude $H_{max}$ which the ejected gas reaches is determined by the initial velocity $v$ acquired at the moment the shock wave passes and is given approximately by $H_{max} \simeq v^2/2g \simeq 3000$ km. To estimate the radiation flux from the surface of the expanding gas, it is necessary to determine how the thickness and transverse size of the optically dense region change. The thickness $L$ of the optically dense layer is found from the condition of transparency: $\kappa_\omega \Delta_L \simeq 1$. The absorption coefficient can be estimated as $\kappa_\omega \propto n(z) T^{-1} e^{-E_{eff} - \hbar\omega/kT}$, where $E_{eff}$ is the effective excitation energy of a vibrational transition and $z$ is the coordinate (relative to the center of mass of the moving gas), so that $n \propto e^{-z/\Delta L}$. Substituting $\Delta_L(t)$ and $T(t)$ into the condition of transparency, we obtain an equation for the time-dependence of the thickness $L$ of the optically dense layer:

$$L(\tilde{t}) \simeq L_0 \tilde{t} \left\{ 1 - \frac{\Delta}{L_0} \left[ (5-3\gamma) \ln \tilde{t} + \frac{E_{eff} - \hbar\omega}{kT_0} (\tilde{t}^{3(\gamma-1)} - 1) \right] \right\} \tag{2}$$

where $\tilde{t} = t/t_f \geq 1$. The intensity of the radiation from the expanding gas ejected into the upper atmosphere (in the limit $\hbar\omega \leq kT$) is given by the following expression:

$$I_\omega(\tilde{t}) \propto \tilde{t}^{4-3\gamma} L(\tilde{t}). \quad (3)$$

The transverse size of the radiating region increases as $d \propto t$, and the characteristic expansion time is $t_c \simeq d_0/c_s \simeq 20-30$ s, where $c_s$ is the velocity of sound. The thickness of the layer varies as follows: At the onset of the expansion, when the gas temperature is quite high and the Boltzmann factor $e^{-E_{\mathrm{eff}}/kT}$ does not play a decisive role, the thickness $L$ of the radiating layer increases and, in spite of the decrease in temperature, the intensity of the radiation increases. As the temperature decreases, the Boltzmann factor starts to predominate and, in spite of the expansion, the thickness $L$ starts to decrease and the radiating region collapses. The duration of the radiation is determined from the expression (3) as

$$t_{\mathrm{rad}} \simeq \left[1 + \frac{L_0}{\Delta} \frac{kT_0}{E_{\mathrm{eff}} - \hbar\omega}\right]^{\frac{1}{3(\gamma-1)}} t_f. \quad (4)$$

For the parameters indicated above, $t_{\mathrm{rad}} \simeq 500-1000$ s. Figure 1 displays a curve of the intensity of the radiation determined in accordance with the model described above. The computed duration of the flash is $\sim 10$ min, which agrees well with the recorded duration of the main peak in the light curve. Therefore we conclude that the source of the main maximum is radiation from the heated, optically dense gas ejected into the upper atmosphere.

We call attention to a fundamental difference between Pc2 and the main maximum: The source of the main maximum — the gas ejected into the upper atmosphere — can be seen directly from Earth, while the source of the flash Pc2 is hidden behind the limb, and only the radiation scattered in Jupiter's atmosphere is visible, as a result, the intensity of the main peak is much higher than that of the flash Pc2. Moreover, the duration of the main maximum is approximately an order of magnitude longer than that of Pc2. This is associated with the fact that the characteristic cooling time of the expanding gas increases with time, varying from several seconds at the moment the shock wave passes up to several tens of seconds at a late stage of cooling.

We note that the proposed model easily explains the following observational result:[3] According to observations,[3] the maximum altitudes reached by the ejected gas for different falling fragments were approximately the same $h_m \simeq 3000$ km.

Indeed, the temperature of the ejected gas depends strongly on the velocity of the shock wave. The initial temperature $T$ of the gas ejected by a shock wave propagating with velocity $D \simeq 12-14$ km/s is of the order of $T_{\max}$ ($T \simeq 5000-7000$ K), and the maximum ejection altitude $H_{\max} \simeq D^2/2g \simeq 2500-3500$ km $\simeq h_m$. This gas, which is ransparent initially, becomes optically dense at a late stage of cooling. If the initial temperature of the ejected gas is much higher than $T_{\max}$, however, then the gas is ejected from quite high altitudes ($h \geqslant 150$ km above the 1 bar level), and its initial density is very low. At the later stage of expansion of this gas, when its temperature reaches 2000–3000 K, its density is too low to give optical thicknesses $\tau_{\mathrm{opt}} \geqslant 1$. Gas ejected with a relatively low initial temperature $T \leqslant 3000$ K), however, cools quite rapidly and also becomes transparent.

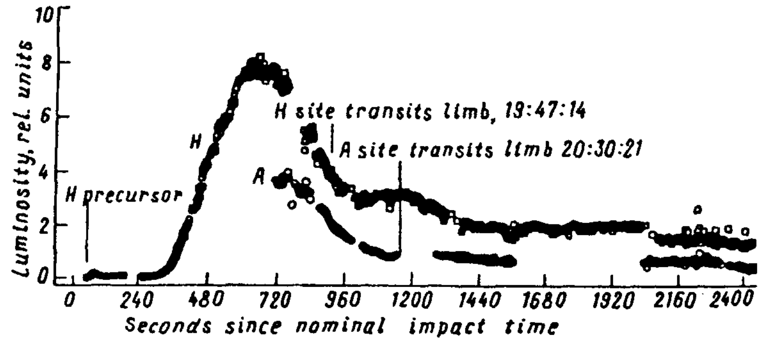


FIG. 2. Light curves for fragments $A$ and $H$ at the wavelength $\lambda=10$ $\mu$m.[15]

We now consider one other important feature of Earth-based observational data: The delay between the time a comet fragment falls and the moment at which the main maximum starts. This delay is determined by expansion and cooling processes in the ejected gas. If the initial gas density is sufficiently high, then for different falling fragments the gas ejected from the same altitude becomes optically dense at different times. Therefore the delay will depend on the energy of the comet fragment. When the initial density of the ejected gas (and, correspondingly, the energy of the fragment) is less than some threshold value, however, the gas will never become optically dense.

The formation of a plateau was observed in the infrared light curves 15–20 min after the comet fragments fell. This is apparently associated with the emergence on the visible side of Jupiter of the locations at which the fragments fell (see Fig. 2 in Ref. 15). As a result, the thermal radiation of the atmosphere heated by both the explosion and the gas ejected into the upper atmosphere and falling back down can make an additional contribution to the total radiation from Jupiter.

In conclusion, we shall discuss the most widely accepted interpretation of the main peak in the light curves obtained during the impact of the comet fragments. The simple model proposed in Ref. 9 attributes the main peak to thermal radiation produced by the gas ejected into the upper atmosphere during the explosion of the fragment and dropping back down. In accordance with the calculations presented in Ref. 9 , the gas falling back into the atmosphere heats the atmosphere to temperatures of several thousands of degrees at altitudes of 250–350 km above the 1 bar level. In Ref. 9 it was assumed that the heated atmospheric layer radiates as a black body, but simple estimates show that the optical thickness of such a layer is very small and that the heated gas is a volume emitter. We note that there is another reason why this mechanism cannot explain the main peak.

As one can see from Fig. 2, the delay $t_D$ between the time a fragment falls and the onset of the main peak is equal to approximately $t_D \simeq 300$ s (for fragment $H$). The results of the numerical gasdynamic modeling show that the deceleration of the falling gas and the subsequent heating of the atmosphere occur at alitudes $h_m \sim 300$ km above the 1 bar level. According to Fig. 2, by the time $t=t_D$ after a fragment has fallen, the heated atmospheric gas is located far behind the limb of Jupiter (the distance between the location where a fragment has fallen and the linear line of sight to Earth is about 1000 km$>h_m$). Therefore the heated atmospheric gas cannot be responsible for the main maximum in the infrared light curves.

It is important to note that the model proposed in Ref. 9 is very sensitive to the angle of the location where a fragment has fallen behind the limb, since for large angles the atmosphere heated by the gas falling back down is located far behind the limb right up to the onset of the main peak (the typical delay time $t_D=300-400$ s for most fragments; for fragment $C$ the delay time is even shorter: $t_D\simeq200$ s). In Ref. 9 the infrared curve was analyzed only for fragment $R$. The location where this fragment fell was located 4.8° behind the limb (for comparison, this angle is $\simeq$9.6° for fragment $H$). For this reason, the impact location of fragment $R$ emerged on the visible side of Jupiter approximately at the time that the strong heating of the atmosphere by the falling gas started. Apparently, this is why the light curve of the fragment $R$ was chosen in Ref. 9 — to illustrate the model of heating of the atmosphere by the gas falling back down.

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