Collision of Comet Shoemaker–Levy 9 with Jupiter: interpretation of optical observations

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Optical observations of Jupiter during its collision with Comet Shoemaker–Levy 9 are analyzed. An explosion model for the release of energy during the stopping of fragments of the comet in the Jovian atmosphere yields a satisfactory explanation of the observed optical effects. It also yields satisfactory values for the energy and size of the fragments. © *1995 American Institute of Physics.*

Comet Shoemaker–Levy 9 collided with Jupiter in July of 1994. The collision process was observed from the earth and also from the Hubble and Galileo space vehicles. Extensive experimental information on the interaction of the comet with Jupiter was obtained. A qualitative model proposed in Ref. 1 explained the first observational data. That model is based on the assumption of an explosive release of energy as the fragments of the comet are stopped in the atmosphere, with the result that an intense shock wave forms. It was shown that the upward propagation of this shock wave, in the direction of decreasing atmospheric density, results in a pronounced acceleration of the shock wave. A layer of heated, weakly ionized gas is pushed into the upper atmosphere of Jupiter. We believe that this gas layer is responsible for observational effects. Fairly comprehensive quantitative data from optical observations of Jupiter during the collision have recently become available; some of these results are reported below.

The stopping of fragments of the comet in the Jovian atmosphere was observed directly from the Galileo space vehicle. Brief bursts in the optical and IR regions were detected upon impact of some of the fragments. Figure 1 shows the time evolution of the radiation flux density at the wavelength $\lambda = 945$ nm as detected on the Galileo at the time of impact of fragments G, H, L, and $Q1$ (Ref. 2). The intensity of the emission initially rises rapidly (with a time scale of 1–2 s), then a plateau forms (at 10–15 s), and then there is a rapid decay to a background level over about 30–40 s. The probable explanation of the several pronounced peaks in the intensity for fragment $Q1$ is that this fragment $Q1$ actually consisted of several smaller fragments, which entered the Jovian atmosphere at times spread out over a certain interval. Figure 2 shows the evolution of glowing formations which appeared at the limb of Jupiter after the impact of fragment G. The glowing formation which results from the collision rises to a height $\simeq 3300$ km and has a length scale of several thousand kilometers. This formation remains an effective

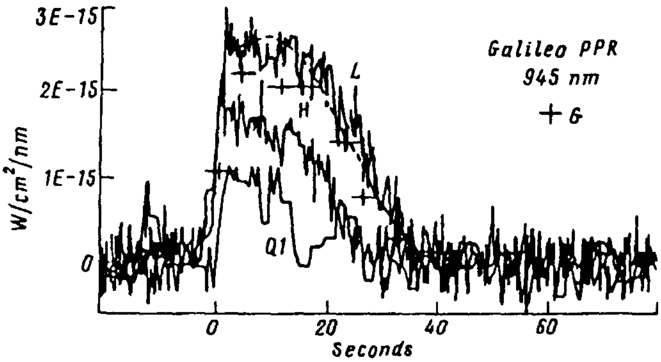

FIG. 1. Time evolution of the radiation flux density at the wavelength $\lambda = 945$ nm detected on the Galileo space vehicle (1.5 AU from Jupiter) at the time of impact of fragments G, H, and Q of Comet Shoemaker–Levy 9. Dashed curve—Calculation from Eq. (3) for an explosion with an energy $E_0 \sim 10^{29}$ erg; plus signs—fragment G.

emitter for about 15 min over a broad wavelength range (from the IR to the UV). This formation has clearly defined boundaries, and its thickness initially increases and then decreases, while its transverse dimension continuously increases. Figure 3 shows the time evolution of the spectral intensity of the IR emission ($\lambda = 10$ μm) of glowing formations which arose in the collisions of fragments H and $Q1$. So far, there has been no quantitative interpretation of these data.

In the present letter we develop the model proposed in Ref. 1 further, and we compare results predicted by this model with observational data.

In a later stage of the stopping of a fragment in the atmosphere, the energy release proceeds in accordance with $E(t) \simeq E_0(t/\tau_s)/(1+t/\tau_s)$, where E_0 is the kinetic energy of the fragment, $\tau_s \simeq \Delta/v_0 \simeq 1$ s is a time scale of the energy release, and $\Delta \simeq 70$ km is the scale height of the Jovian atmosphere. For the fairly large fragments of Comet Shoemaker–Levy (with a diameter $D_i \simeq 0.5$–2 km and an energy $E_0 \simeq 10^{27}$–10^{30} erg; we are assuming that the comet consists of ice), most of the energy is released in the height interval -200 km $\leqslant h_s \leqslant -50$ km, where the gas pressure is $p_s \simeq 5$–50 bar, and the density is $\rho_s \simeq 10^{-4}$–10^{-3} g/cm^3 (Ref. 3, for example). The energy release occurs in a

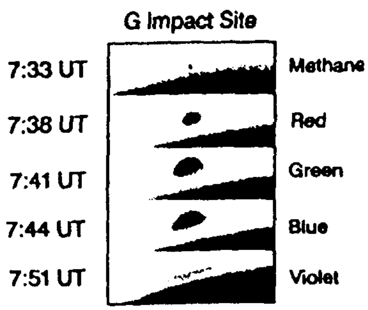

FIG. 2. Evolution of a glowing formation which appeared at the limb of Jupiter after the impact of fragment G. This series of photographs, taken by the Hubble space telescope, gives an idea of the luminosity and shape of this object in various parts of the spectrum at various times.

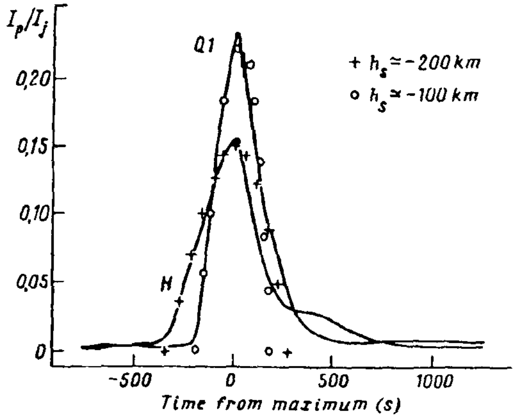

FIG. 3. Time evolution of the spectral intensity of the IR emission ($\lambda = 10$ μm) of glowing formations which appeared upon the impact of fragments H and $Q1$ (these photographs were taken at the Calar Alto Observatory in Spain). The spectral intensity of the emission has been normalized to the flux density of the thermal emission of the Jovian disk at the specified wavelength. The results calculated from Eq. (5) and shown here correspond to explosions at heights $h_s \simeq -200$ km (+) and $h_s \simeq -10$ km (○).

volume $V_E \simeq D_i^2 \Delta$, in which a pressure $p_E \sim (\gamma - 1)E_0/V_E \sim (10^5 - 10^6)p_s$ is reached (the energy expended on the destruction and evaporation of a fragment does not exceed 0.1% of E_0; i.e., essentially all the energy released in the collision is expended on heating gas).

The evolution of the shock wave formed as the result of such an energy release, over times $t \gg \tau_s$, can be described through the use of a self-similar solution of the problem of strong explosions.[4] For an energy $E_0 \simeq 10^{30}$ erg, for example, $\simeq 80\%$ of the kinetic energy of the fragment is released by a time $t_0 \simeq 4\tau_s$, and the shock front traverses a distance $R_f \simeq (E_0/\rho_s)^{1/5} t_0^{2/5} \simeq 60$ km $\gg D_i$. The time and length scales of the energy release thus drop out of the problem, and the latter becomes approximately self-similar. We should point out that at this time we have $R_f \gg \Delta$, and the approximation of a spherical explosion is completely justified. The velocity D_f of the shock wave is $D_f \simeq 2/5 R_f/t_0 \simeq 6$ km/s, and the temperature of the shock-compressed gas is $T_f \simeq 1000$ K. The gas temperature increases very rapidly with distance from the shock front toward the center of the explosion: $T \simeq (R_f/r)^{(2\gamma+1)/(\gamma-1)} T_f$.

The gas behind the shock front radiates with a transparency temperature $T_{\rm opt} \simeq 15\ 000$ K (Ref. 5). The layer of gas moving behind the shock front, at a temperature $T_{\rm opt}$, cools off as a result of the emission, leading to the formation of a cooling wave as the shock wave weakens. This cooling wave is traveling with respect to the moving gas, toward the center. Its velocity is $u \simeq 2\sigma T_{\rm opt}^4 / p_s (1 - T_{\rm opt}/T_*)^{-1}$, where $T_* \gg T_{\rm opt}$ (Ref. 5). At the heights at which most of the energy release occurs, this velocity is $u \simeq 1$ km/s. Consequently, the time over which the fireball formed in the explosion radiates can be estimated to be $R_f/u \simeq 50$ s. As the cooling wave contracts toward the center, the effective area of the radiator decreases. Here are the equation of motion of the front of the cooling wave, $r_{\rm opt}(t)$, and a solution of this equation:

$$\frac{dr}{dt} = \frac{2}{5} \frac{2}{\gamma+1} \frac{r}{t} - u, \tag{1}$$

$$r_{\rm opt}(\tau) = r_0((1+\beta)\tau^{\frac{4}{5(\gamma+1)}} - \beta\tau), \tag{2}$$

where $\beta = 5(\gamma+1)/(5\gamma+1)ut_0/r_0$; $\tau = t/t_0$; and r_0 is the radius of the layer, which has a temperature T_{opt} at the time t_0. For $E_0 \simeq 10^{30}$ erg we would have $r_0 \simeq 40$ km. This explosion and the formation of radiating plasma occur under the cloud cover, which is at a height $h \simeq 0$ km. Direct emission from the burst is completely screened (the optical thickness of the clouds for $\lambda \leq 1$ μm is greater than 15; Ref. 6). The radiation thus escapes outward only through an aperture, $d \simeq 5D_i$ in diameter, which forms in the cloud cover upon impact of the fragment. In this case the spectral density of the radiation satisfies $I_\lambda \propto \Omega = d^2/h_s^2$, and the radiation flux density which can be detected at Galileo is

$$I_\lambda(t) \simeq \frac{8\pi c k T_{opt}}{\lambda^4} \frac{r_{opt}^2(t)}{R_{JG}^2} \Omega. \tag{3}$$

Figure 1 shows a plot of $I_\lambda(t)$. For $E_0 \simeq 10^{29}$ erg, it gives a good approximation of the intensity of the radiation detected upon the impact of fragment L. Since we have $I_\lambda^{max} \propto E_0^{2/5}$, we can easily estimate the energy and size of fragments G and H: 5.7×10^{28} erg ($D_i \simeq 1.7$ km) and 2.8×10^{28} erg ($D_i \simeq 1.3$ km), respectively. The error in the determination of the energy ($\delta E/E$) and in the determination of the size ($\delta D_i/D_i$) of the fragments of the comet is nonzero because of the high noise level in the radiation detected. In our case we have $\delta E/E \simeq 0.5$ and $\delta D_i/D_i \simeq 0.15$. Possible absorption of the radiation at these wavelengths in the Jovian atmosphere may have the consequence that the actual energy of the fragments is slightly larger than that calculated.

Several authors[1,7] associate the burst of emission detected at Galileo with the emission from a shock wave which arises when a fragment enters the dense lower layers of the atmosphere. In that case, however, the light pulse would have a shape other than that observed: Instead of a plateau, there would be a pronounced increase (by about an order of magnitude) in the intensity[7] and a sharp decay (over a time $\simeq 3$ s). Furthermore, the duration of the pulse would not be more than 5–6 s in this case.

We turn now to the shock wave which arises from the explosion and which travels upward, in the direction of decreasing density. As was shown in Ref. 8, the shock wave begins to accelerate at heights $\simeq -50$ km in the Jovian atmosphere (for an explosion energy $E_0 \simeq 10^{30}$ erg and an explosion height $h_s \simeq -200$ km); the ionization behind the front of the shock wave increases; and the plasma behind the shock front becomes optically dense, beginning at heights $\simeq 100$ km, about 200 s after the explosion. The subsequent acceleration of the shock wave leads to full ionization of the gas behind the front. The electron density then decreases along with the density of the atmosphere, setting an upper boundary on the optically dense plasma. As a result, a layer of shock-compressed, optically dense plasma forms; it has upper and lower boundaries and is moving upward at an average-mass velocity $\simeq 15$ km/s. Immediately after the passage of the shock wave, the thickness of the optically dense plasma layer which has formed, L_0, is about 30–40 km, its transverse dimension is $d_w \simeq 200$ km, and the average temperature over the layer is $T_0 \simeq 5-6$ eV. The subsequent motion of the expanding gas is described by a self-similar solution.[9] According to that solution, the gas which is compressed by the shock wave, and for which the variations have an initial length scale $\Delta_{l0} \simeq (\gamma - 1/)(\gamma+1)\Delta$, begins to expand as it moves just behind the shock front. This expansion initially proceeds in a quasi-1D fashion, and the density is described by $n \sim (t/t_f)^{-1}$, where t_f is a time scale which depends on the height: For the plasma layer which we are discussing, it is[8] $t_f \simeq 10$ s. The length scale Δ_l of the layer increases in accordance with $\Delta_l \simeq \Delta_{l0}(t/t_f)$. The temperature falls off because of adiabatic expansion and also because of radiation in the upper part of the layer, where the initial temperature is high. As a result, the temperature in the layer equalizes fairly rapidly and decreases to 2–3 eV. From this time on, the radiation has only a weak effect on the temperature (since the time scale of the radiative cooling, $\tau_{\mathrm{irr}} \propto T^{-3}$, becomes far longer than t_f[8]), and the temperature is determined only by adiabatic expansion, which becomes three-dimensional: $n \propto t^{-3}$, $T \sim n^{\gamma-1} \propto n^{-3(\gamma-1)}$. Several tens of seconds after it forms, the shock-compressed layer reaches heights at which its radiation becomes directly observable from the earth, and the temperature of the layer is $\simeq 1$ eV. The maximum height reached by this ejected layer is set by the gravitational force and is about $H_{\max} \simeq 4000$ km. To estimate the flux density of radiation from the surface of the expanding plasma we need to determine how the thickness and transverse dimension of the optically dense region vary. The boundary $\tilde{z}$, which determines the thickness of this region, is found from the condition $\kappa_\omega \Delta_l \simeq 1$. The absorption coefficient is $\kappa_\omega \sim n(z) T e^{-(I-\hbar\omega)/kT}$, where z is a coordinate (with respect to the center of mass of the moving gas), and $n \sim e^{-z/\Delta_l}$. Substituting $\Delta_l(t)$ and $T(t)$ into the transparency condition, we find an equation for the coordinate of the upper boundary of the transparency region, $\tilde{z}$:

$$\tilde{z}(\tau) \simeq L_0 \tau \left\{ 1 - \frac{\Delta_{l0}}{L_0}(\alpha\gamma - 1)\ln \tau - \frac{\Delta_{l0}}{L_0}\frac{I-\hbar\omega}{T_0}\left(\tau^{\alpha(\gamma-1)} - 1\right) \right\}. \tag{4}$$

Here $\tau = t/t_f$, and the coefficient α varies from one at the beginning of the expansion to $\simeq 3$ at later times. The intensity of the emission (at frequencies $\hbar\omega \ll kT$) from the expanding plasma ejected into the upper atmosphere is

$$I_\omega(\tau) \sim \tau^{1-\alpha(\gamma-1)} \tilde{z}(\tau). \tag{5}$$

The transverse dimension of the emitting region increases: $d_w \propto t$. The time scale is $t_w \simeq d_w / c_s \simeq 20$–$30$ s, where c_s is the sound velocity. The thickness of the layer varies in the following way. At the beginning of the expansion, while the temperature is still fairly high, and recombination not very important, the thickness of the radiating layer increases. Despite the decrease in temperature, the emission intensity rises. As the temperature decreases, recombination in the plasma starts to play a governing role, and the transparency boundaries $\tilde{z}$ begin to move opposite each other, despite the expansion; the emission zone "collapses." In this model the maximum thickness of the glowing formation reaches 1000–2000 km, and its maximum transverse dimension is ~3000–5000 km for fragments with energies $E_0 \simeq 10^{28}$–10^{30} erg.

At the time the emitting region collapses, the rate of recombination processes is still high enough to maintain thermodynamic equilibrium of the plasma.

Figure 3 shows results calculated on the radiation flux density from this model in comparison with observations during the impact of fragments H and $Q1$ of the comet.[12,13] The energies of the fragments are 10^{29}–10^{30} erg for H and 10^{28}–10^{29} erg for

$Q1$, which correspond to the following depths of penetration into the atmosphere: -150 km $\leqslant h_s \leqslant -200$ km (for H) and -100 km $\leqslant h_s \leqslant -150$ km (for $Q1$).

The reason for the faster increase in I_ω for fragment $Q1$ is the relation $I_\omega \propto L_0$ and L_0 increases with increasing height at which the explosion occurs.[8] The duration of the burst is $\propto L_0/\Delta_{I0}$ and falls off with increasing height of the explosion, despite the increase in L_0. The reason is that the shock-compressed layer forms at lower heights for explosions which are less deep, and the scale height of the Jovian atmosphere, Δ, increases with decreasing height.

The onset of the glowing formation was explained in Refs. 7, 10, and 11 on the basis of the formation of a gas jet which is ejected into the upper atmosphere of Jupiter upon the impact of the fragment. In that case, however, the ejected mass of gas would not have had a lower boundary clearly observable from the Hubble space telescope (i.e., there would have been no gap between the limb and ejected gas, although one is clearly present in Fig. 2). The luminosity of the jet would have to fall off rapidly with increasing height, and this result is again at odds with Fig. 2. Furthermore, the gas temperature in this jet is low ($T \leqslant 1000$ K, according to the calculations of Ref. 11), and the density is so high ($\sim 10^{12}-10^{14}$ cm^{-3}; Ref. 11) that the ejected gas jet would be optically transparent and could not lead to the radiation flux density detected.

Simple estimates show that attempts to explain the observed burst of emission on the basis of a scattering of sunlight by dust ejected along with the gas during the impact, as proposed in Ref. 10.

For fragments H and $Q1$ we see the formation of a "plateau" about 15–20 min after the impact in Fig. 3. The probable explanation is that the points at which these fragments are incident appear on the visible side, and thermal emission from the atmosphere heated by the explosion can make an additional contribution (on the order of a few percent) to the total emission of Jupiter at this wavelength.

In summary, the model of an explosive release of energy provides the first successful quantitative explanation of several pieces of observational data obtained during the collision of certain fragments of Comet Shoemaker–Levy 9 with Jupiter. Other fragments of this comet interacted with the Jovian atmosphere in a similar way.

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