Collision of the comet with Jupiter: explosion in an inhomogeneous atmosphere

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The comet Shoemaker–Levy 9 collided with Jupiter in July of 1994. The theory of powerful explosions in an inhomogeneous atmosphere is used to interpret the first observations of bursts of optical and IR emission and bursts of rf emission in the decameter range accompanying the stopping of the fragments of the comet in the Jovian atmosphere. These observational results may constitute the first experimental confirmation of this explosion theory. © *1994 American Institute of Physics.*

The back side of Jupiter was bombarded by fragments of Comet Shoemaker–Levy 9 from 16 to 22 July 1994. The stopping of an individual fragment in the atmosphere was accompanied by the liberation of a colossal amount of energy. At the typical values of the properties of a fragment—a density $\rho_i \simeq 1$ g/cm^3 (ice), a diameter $D_i \simeq 0.3$–3 km, and an incident velocity $v_i \simeq 65$ km/s—an energy $E \sim 10^{27-30}$ erg was released. Since the collision occurred on the back side of Jupiter, the collision itself was inaccessible to direct observations from the earth. There is accordingly particular interest in reconstructing a picture of the collision from bits and pieces of indirect data: from the short bursts of optical and IR emission visible from behind the limb and from the pulses of rf emission in the decameter range which were observed by certain stations. Figure 1 shows photographs of Jupiter in the IR region at a wavelength of 2.3 μm at various times after the collision of one of the fragments. We can clearly see the formation of a burst at the edge of the limb; this burst dies out after about 20 min. According to preliminary data, the collision of several of the fragments of Comet Shoemaker–Levy with Jupiter was also accompanied by an intensification of the decametric emission from Jupiter. In this letter we offer an explanation for these observational data.

As a fragment of a comet enters an atmosphere, it begins to be slowed significantly when the mass of atmospheric gas displaced by the fragment becomes comparable to the mass of the fragment itself. In an exponential atmosphere, significant slowing begins in the dense layers, with a gas density

$$\rho_s \simeq \frac{\rho_i D_i \cos\theta}{3\Delta}. \qquad (1)$$

(The scale height Δ of the Jovian atmosphere depends strongly on the height h, which is

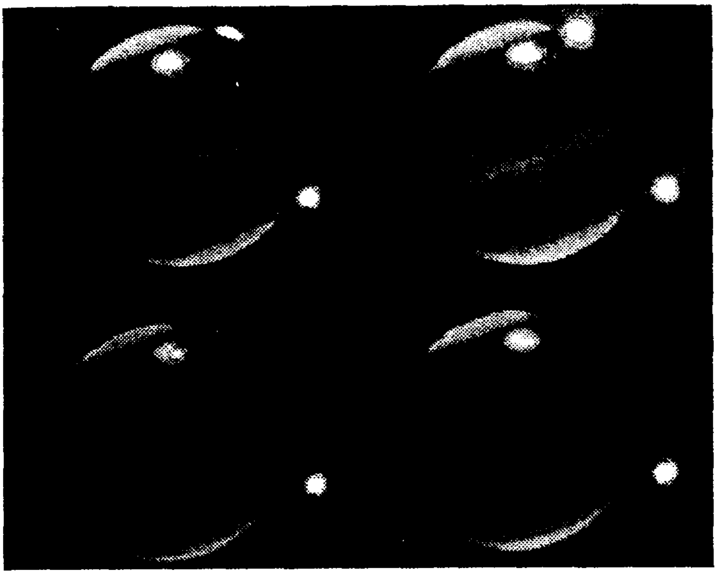

FIG. 1. Images of Jupiter in the IR region ($\lambda=2.3$ μm) after a collision with one of the fragments (fragment H) of Comet Shoemaker–Levy 9. These photographs were taken at the Calar Alto Observatory in Spain. The formation of a burst of IR emission at the edge of the Jovian limb can be seen. The duration of the burst was about 30 min. The time interval between successive frames is about 10 min. The bright source in the upper left corner of each frame is a satellite of Jupiter. The large bright spot on the disk is also a feature resulting from the explosive stopping of one of the large fragments of the comet.

reckoned from the level at which the pressure p of the surrounding gas is 1 bar; in particular, at heights with $p>1$ bar we have $\Delta\simeq75$ km, while at heights with $p\leqslant1$ bar we have $\Delta\simeq25$ km.) Here θ is the angle (measured from the local vertical) at which the fragment is incident. Assuming $\rho_i\simeq1$ g/cm^3, $D_i\simeq1$ km, $\theta\simeq45°$, and $\Delta\simeq75$ km, we find that the stopping of the cometary fragment occurs mostly at a density $\rho_s\simeq2\times10^{-3}$ g/cm^3 of the surrounding medium and at a pressure $p_s\simeq35$ bar. These figures correspond to a height $h_s\simeq-160$ km in the Jovian atmosphere. The detailed calculations of Refs. 1–3, which incorporate the destruction of the cometary material and the change in its shape in the course of the stopping, may lead to some increase in the height of the explosion, but that correction would not alter the qualitative conclusions drawn below.

Since most of the energy release occurs over a time $\tau_s\sim\Delta/v_i\simeq1$ s, the stopping of Comet Shoemaker–Levy in the Jovian atmosphere can be treated as an explosion. Using the exact solution of the problem of a point explosion,[4,5] one can easily show that the duration of the strong shock wave, τ_{sw} (the time over which the pressure behind the shock front is much higher than the pressure ahead of it), is significantly longer than the time scale of the energy release τ_s: $\tau_{\text{sw}}/\tau_s\geqslant10^3$. For these parameter values of the energy release, the length scale of the problem satisfies $(E/p_s)^{\frac{1}{3}}\gg\Delta$. The effect of the inhomogeneity of the Jovian atmosphere on the propagation of the shock wave resulting from the explosion of the fragment thus becomes the governing effect.[6] Since most of the

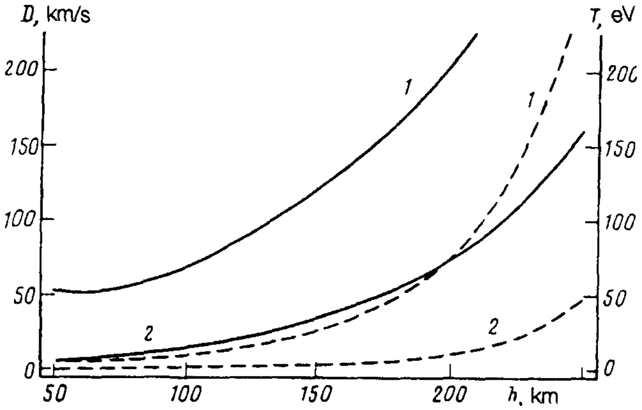

FIG. 2. The velocity of the shock wave, D (the solid curves), and the temperature T behind the shock front (the dashed curves) versus the height h above the 1-bar level in the Jovian atmosphere. 1—Explosion of the fragment at a height $h_s = 0$ km ($p_s \simeq 1$ bar); 2—explosion of the fragment at a height $h_s = -200$ km ($p_s \simeq 60$ bar). The energy of the explosion is 10^{29} erg.

stopping and the explosion of the fragment occur over a length scale $\simeq \Delta$, and since the basic processes associated with the inhomogeneity of the atmosphere are manifested at length scales much larger than Δ, the explosion of the fragment can be treated as a point explosion. One more factor which makes the energy release a local effect might be rapid destruction of the fragment, which leads to a sharp increase in the drag in the stopping of the fragment.

According to the solution of the problem of the propagation of a shock wave caused by a powerful point explosion in an inhomogeneous (exponential) atmosphere,[6] the upper part of the shock front is accelerated during the propagation, in the direction of the vertical decrease in the density, in accordance with

$$D \simeq \sqrt{\frac{3(\gamma+1)^2}{8\pi} \frac{E}{\rho_s R^3}} \exp^{R/2\Delta}, \tag{2}$$

where D is the velocity of the shock wave, R is the distance between the shock front and the point of the explosion, and γ is the ratio of specific heats. Essentially the entire mass of gas compressed by the shock wave is in a thin layer δ behind the shock front and is moving at a mass velocity close to the velocity of the shock wave. The gas temperature T behind the shock front in this layer is proportional to D^2 in the limit of high shock-wave velocities. Figure 2 shows plots of $D(h)$ and $T(h)$ in the Jovian atmosphere (85% H_2, 15% He) for an explosion with an energy $E \sim 10^{29}$ erg occurring at a height $h_s = -200$ km. We see that, beginning at heights ~ 175 km, the gas temperature T behind the shock front is $\geqslant 2$ eV, and the gas behind the front is highly ionized. During the explosion of a cometary fragment, a large fraction of the gas in the shock-compressed layer is thus ionized by the viscous shock. It is therefore capable of emitting in the optical and rf regions. As it propagates upward, the shock wave goes into a region of lower density, in which the hydrodynamic approximation no longer applies. The transition occurs at heights $h \sim 500$ km. The shock-compressed layer continues its inertial motion at an average mass velocity ~ 50 km/s. By this time, the properties in the shock-compressed layer have reached the following state: The typical thickness of the region containing the bulk of the ionized gas is $\delta \simeq 10$ km; the typical diameter is $\simeq 2\pi\Delta \sim 500$ km; the average temperature over the layer is $\langle T \rangle \simeq 4$ eV; the average mass density is $\langle \rho \rangle \simeq 5 \times 10^{-7}$ g/cm^3; and the average electron density is $\langle n_e \rangle \simeq 10^{17}$ cm^{-3}. Consequently, as it accelerates in an atmosphere with a rapidly decreasing density, the shock wave can be an effective source of a shock-compressed, heated plasma at heights of hundreds of kilometers, i.e., beginning at those heights at which the emission from this plasma becomes accessible to direct observation from the earth.

Since the dimensions and density of the fragments can vary widely ($D_i \simeq 0.3$–3 km, $\rho_i \simeq 0.3$–3 g/cm^3), the height of the explosion may also vary. (According to preliminary observational data, the depth to which the cometary fragments penetrated into the Jovian atmosphere ranged from -200 km to 25 km.) As the point of the explosion rises, the shock wave reaches a velocity on the order of 50 km/s (sufficient for the onset of intense ionization behind the shock front) while traversing smaller intervals of height, as can be seen from Fig. 2. As a result, the mass of ionized gas ejected into the upper layers of the atmosphere increases. The reason for the more rapid increase in the velocity of the shock wave in this case is that this velocity is inversely proportional to the square root of the density of the atmosphere at the level of the explosion, which falls off exponentially with increasing height. Consequently, the relatively small fragments of Comet Shoemaker–Levy ($D_i \sim 300$ m), whose stopping and explosion occur at large heights, may prove more effective than large fragments in terms of their observational consequences.

The ejected layer of heated gas is initially an effective radiator in the optical and IR regions: The ratio δ/l_λ, where l_λ is the range of photons with a wavelength λ, has values $\simeq 5 \times 10^3$ and $\simeq 25$ for photons with wavelengths of 3 and 0.3 μm, respectively. As the gas expands, the parameter δ/l_λ decreases; the value $\delta/l_\lambda \simeq 1$ is reached in about 5 min for $\lambda = 0.3$ μm and 30 min for $\lambda = 3$ μm. These times determine the duration of the period during which this layer emits at its maximum brightness at the given wavelength. The geometry of the collision of the fragments of the comet with Jupiter was such that the time at which the shock-compressed layer reaches the limb (when the ejected gas become accessible to earth-based observations) ranges from 10 to 30 s. Consequently, a prolonged burst of emission in the IR region can indeed by observed at the earth, and the burst of emission in the optical region may or may not be observed. Judging from the photograph in Fig. 1, the typical size of the region emitting the IR region is a few thousand kilometers. The original compressed layer of gas, expanding into vacuum, reaches such dimensions in ~ 100 s, remaining an effective emitter in the IR region in the process. Estimates of the layer expansion time and the effective luminosity thus agree well with the observed duration of the burst.

We should also mention that, in addition to the heated and ionized plasma (if the explosion occurs at a height below the 1-bar level), a large mass of the gas forming the cloud cover, at a temperature $\leqslant 1000$ K, will be ejected into the shock-compressed layer in the upper atmosphere of Jupiter. (The reason is that the clouds are at a level at which the pressure of the surrounding atmosphere is ~ 1 bar, and the velocity of the shock wave at these heights is still small, as can be seen from Fig. 2.) In a gas with this temperature, vibrational levels of molecules forming the cloud cover (ammonia, methane, and other hydrocarbons) are effectively excited, so they may also emit in the IR region as the ejected gas expands.

Perturbations of the rf emission in the decameter range were observed at the times at which some of the fragments of the comet were incident. According to preliminary data [RATAN-600 (Russia) and several observatories in the US, Japan, France, and elsewhere], bursts in the intensity of the rf emission at frequencies of 15–30 MHz (reaching levels of 10–50% above the background) were detected. They lasted a few minutes. The source of the observed increases in the intensity of the decameter radiation may be the plasma of the shock-compressed layer, heated to high temperatures. A plasma of this sort at a large height in the Jovian magnetic field being magnetized, might generate cyclotron radiation at frequencies close to those observed.

In summary, we have drawn a picture in which the source of the observed bursts in the IR and decameter regions accompanying the incidence of individual fragments is a shock-compressed layer of heated, ionized gas ejected into the upper layers of the atmosphere by a shock wave which is formed upon the explosion of the fragment in the Jovian atmosphere. Note that a substantial acceleration of the shock wave during its propagation, due to the pronounced (exponential) inhomogeneity of the atmosphere, and possible effects in the ionosphere and magnetosphere related to this acceleration begin to be seen only after the shock wave has traversed distances greater than a few times Δ. These effects would thus never be observed under the conditions at the earth, since they would be realized only during very powerful explosions ($E \geqslant 10^{26}$ erg$\approx 2\times 10^3$ Mton). Fortunately, no such explosions have ever occurred at the earth. The energy at the most powerful explosion, which has ever been conducted at the earth (in tests in Novaya Zemlya), was 50 Mton. The power of the explosion of the famous Tunguska meteorite was estimated to be also about 50 Mton. Consequently, observational data on the collision of Comet Shoemaker–Levy with Jupiter may constitute the first indirect confirmation of the theory of point explosions in an inhomogeneous atmosphere.

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[1] D. A. Crawford *et al.*, Geophys. Res. Lett. (1994), in press.
[2] V. A. Ivanov and H. J. Melosh, Lunar Planet. Sci. **25**, 597 (1994).
[3] B. A. Klumov *et al.*, Usp. Fiz. Nauk **6**, 617 (1994).
[4] L. I. Sedov, *Similarity and Dimensional Methods in Mechanics* (Academic, New York, 1959).
[5] Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic, New York, 1966).
[6] A. S. Kompaneets, Dokl. Akad. Nauk SSSR **130**, 1001 (1960) [Sov. Phys. Dokl. **5**, 46 (1960)].

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