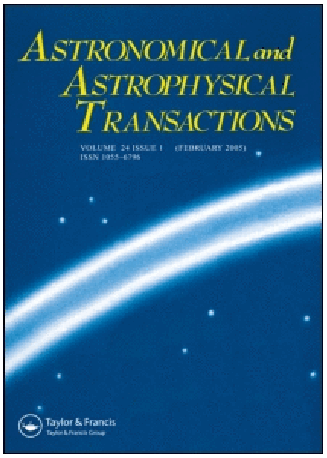

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LIGHT ECHOES FROM EUROPA AND IO DURING EVENTS OF SHOEMAKER-LEVI 9 A AND Q FIREBALLS IN THE JUPITER ATMOSPHERE AND POSSIBLE ORIGIN OF COMET SL-9

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On the basis of speed photoelectric observations of Europa and Io, flashes of fireball in the atmosphere of Jupiter during the fall of fragment A and Q2 of the comet SL-9 were registered. The flash of the A fragment having an amplitude of 0.12 mag and a duration of 0.7 sec was registered on July 16 during observations of Europa. The flash of the Q2 fragment on July 20 having an amplitude of 0.11 mag and a duration of 1.0 sec was registered during observations of Io. Analogous parameters of the second flash were obtained at the Vatican Observatory. The data allowed one to estimate the energy of flashes and fragment radii. Taking into account the paper by Sekanina, we assume that in the fireball light enegry radiation transforms 1% from the kinetic energy of the secondary nucleus of the comet SL-9 during its impact with the Jupiter atmosphere. We have obtained the following estimate for sizes of the secondary nuclei A and Q2 of SL-9: $R(A) = 1.42$ km for $p = 0.3$ g/sm^3 (1.00 km for $p = 1.0$ g/sm^3; $R(Q2) = 0.65$ km for $p = 0.3$ g/sm^3 (0.43 km for $p = 1.0$ g/sm^3). An assumption about possible origin of comet SL-9 was made.

KEY WORDS Comet Shoemaker-Levi 9, Jupiter, fireball, electrophotometry

1 INTRODUCTION

A collision of the comet SL-9 with Jupiter is an outstanding event in the history of human civilization. Twenty secondary nuclei of the comet conserved before it impacted on Jupiter at the speed of 65 km/sec on July 16–22, 1994. As a result of a series of outbursts of the comet SL-9 secondary nuclei on the night side of the planet, light echoes must have been observed and after the reflection from the Galilean satellites (Io, Europa, Ganymed, Callisto) they might be observed from the Earth as a short time increase in brightnesses of the satellites at the moment of outburst of this or that secondary fragment.

With this aim numerous observers (Barwig and Barbantner, 1994; Consolmagno and Menard, 1995; Foust *et al.*, 1994; Woodney *et al.*, 1994; Lassaro *et al.*, 1994; Wasserman *et al.*, 1994; Zhou, 1995; Blanco *et al.*, 1995) within the period from July 16–22, 1994 patrolling of the Jupiter satellites was carried out to register similar light outbursts. It should be noted that preference during the photoelectric observations was given in the first place to Io and Europa, satellites, closest to Jupiter. More distant satellites (Ganymed, Callisto) naturally reflected weaker signals as compared to Io and Europa in the course of registering one and the same flash in the Jupiter atmosphere. This circumstance can be considered as an evidence of the negative result obtained at an attempt to register light echoes from Ganymed and Callisto during the fall of cometary nuclei.

2 OBSERVATIONS AND REDUCTIONS

Jupiter's satellites Io and Europa were observed within the scope of investigations of the comet D/Shoemaker-Levy 9 collision with Jupiter at the Astronomical station of Kiev University in Lisnyki with the electrophotometer mounted on the 0.48 m reflector AZT-14. Our observations were described in papers (Churyumov, 1994; Kleshchonok and Churyumov, 1994). Records of satellites' brightnesses have a high level of noise. Therefore filtration of signals was made by a median filter with a window size of seven points (equal to 0.28 sec) and a linear filter of the same size. Then the pulse counts for the satellite were reduced by the background with the its temporal dependence taken into account. We looked for peaks which were above the triple error value of the signal. Three such events were found out. In Table 1 their parameters are given. Figure 1 shows curves of the satellites brightnesses deviations near the moments of fixed flashes normalized to the maximum of the light curve intensity.

Table 1. Parameters of outbursts

No. events	*Day July*	*Nucleus*	*Starting time*	*Duration sec*	*Amplitude m*	*Phase angle degree*	*Outburst energy* 10^{25} *erg*
1	16	A	$20^h10^m38^s$	0.7	0.16	120	62.0
2	20	Q3?	$19^h32^m09^s$	2.7	0.12	80	9.8
3	20	Q2	$19^h48^m10^s$	1.0	0.11	80	3.2

The total light energy of flash L_i, (here the sign i indicates that light was measured with the filter) was estimated by the formula:

$$L_i = L_{\odot i}\frac{p_\odot}{p_f}\left(\frac{R_\odot}{R_f}\right)^2 \int\limits_{\tau_f} \frac{I_f}{I} dt,$$

where $L_{\odot i}$ is intensity of the Sun light with the same filter, $p_\odot$ and p_f are parts of the satellite surface illuminated by the Sun and the fireball, $R_\odot$ and R_f are the dis-

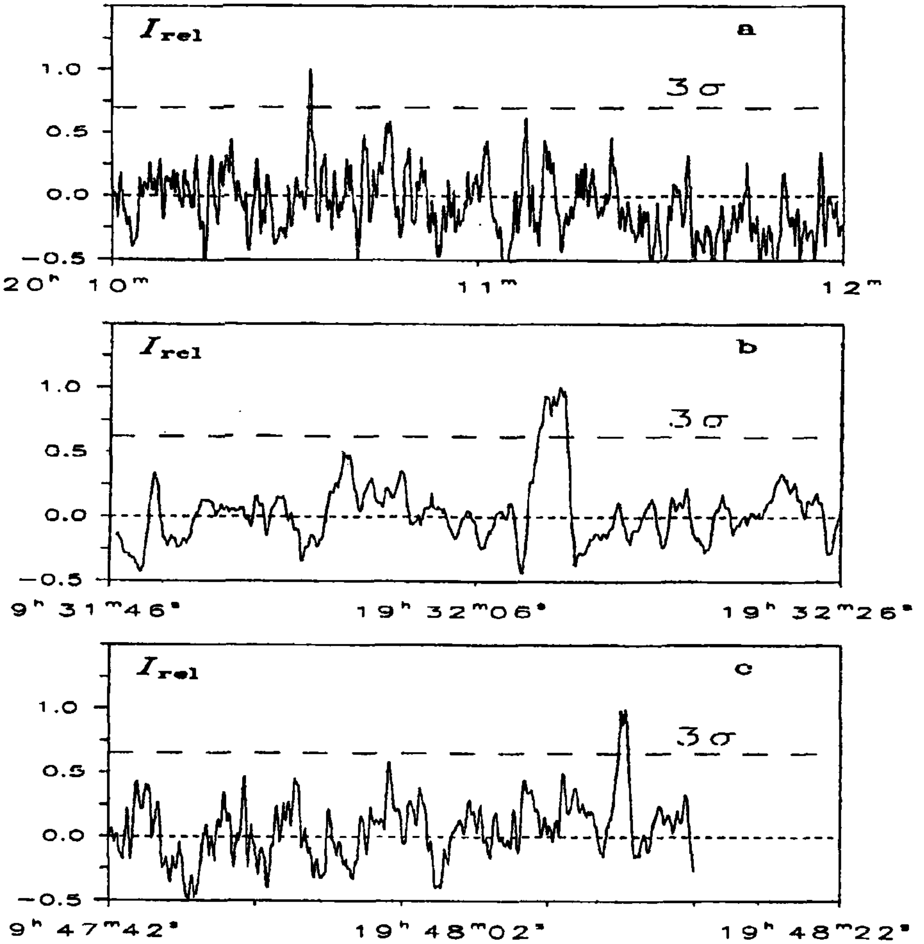

Figure 1 Three flashes of the Jovian satellites during impact events A on July 16 (a), Q3? (b) and Q2 (c) on July 20, 1994.

tances from the satellite to the Sun and the fireball, τ_f is the time interval of the fireball duration, I and I_f are the pulse counts for the satellite and the outburst. In this case we neglected the phase dependence of the reflectivity level and nonuniformity of the satellite surface. The illuminated part of the satellite surface was estimated by the formula:

$$p = \frac{1 + \cos(\varphi)}{2},$$

where φ is the satellite phase angle for the Sun or the fireball. Table 1 below shows the values which were calculated by this method. Figure 1 shows relative curves of the satellite brightness in the region of the selected flashes normalized to the maximum of the outburst curve.

For determination of kinetic energy of the comet nucleus collision it is necessary to include some effects, but their influence can only roughly be estimated. They are:

(1) light extinction in Jupiter's atmosphere. We neglected this effect;

(2) part of the total luminosity energy registered with the filter using. We do not know the real distribution of energy in the fireball spectrum and we assume it to be similar to the solar spectrum;

(3) part of the total kinetic energy which escaped in light radiation. This value was equal to 1% (Sekanina, 1993).

Table 2. Calculated parameters of the comet nuclei

No. Event	*Nucleus*	*Luminosity energy*	*Kinetic energy*	*Mass of nucleus*	*Radius of nucleus km*	
		10^{26} *erg*	10^{28} *erg*	10^{15} *g*	$\rho = 0.3\ g/cm^3$	$\rho = 1\ g/cm^3$
1	A	6.2	6.7	3.7	1.42	1.00
2	Q3?	0.98	1.9	1.1	0.96	0.64
3	Q2	0.32	0.63	0.35	0.65	0.43

Table 2 shows the kinetic energy of possible fireballs calculated under these assumptions. There are parameters of the comet secondary nuclei estimated for two possible values of the comet nucleus density 1 g/cm^3 and 0.3 g/cm^3 (the last value is estimated for the nucleus density of comet P/Halley).

3 DISCUSSION

The first flash was registered by the authors during their observations of Europa on July 16 at $20^h10^m38^s$ with the electrophotometer installed on the AZT-14 telescope through filter V. The moment of observing the flash is close to that predicted by Chodas and Yeomans (Chodas and Yeomans, 1994); O − C = −22 sec. This is considerably less than the error given by Chodas and Yeomans. Therefore this registered moment may be considered as a true moment of an impact of the nucleus A with the Jupiter atmosphere. Parameters of the flash: the outset of the outburst at $20^h10^m38^s$ UT, July 16, the duration of the outburst 0.7 sec, the amplitude 0.16 mag. Shul'man and Nazarchuk monitored the spectrum of Europe during one hour before the fall of the nucleus A with the TV-spectral scanner installed on the 6-m telescope. In the spectrum of the satellite the band near λ490 nm was seen. This fact is evidence of that long before the impact of the visible fragment A a cloud of cometary matter had collided with Jupiter that led to the excitation of the band of unknown cometary species (possible ions of atomic sulfur S^+) whose

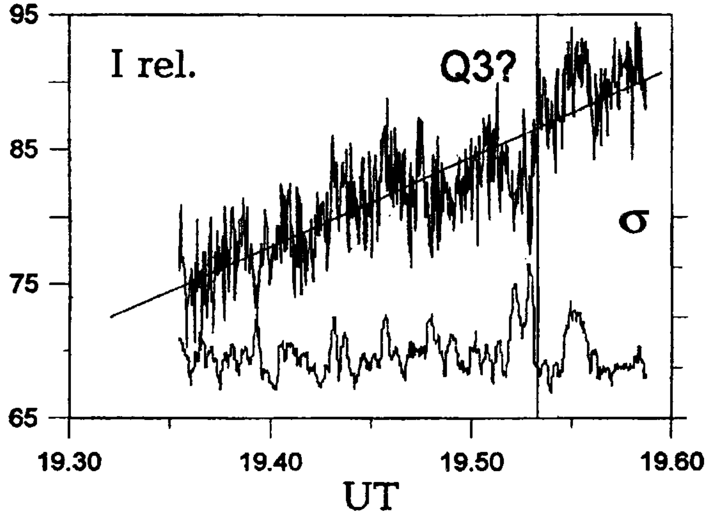

Figure 2 Jupiter radioemission on July, 20 near the moment of possible impact event Q3. The upper curves are records of the radiosignal and its linear aproximation. The lower curve is a deviation of the radiosignal from linear dependence. It is seen that a strong minimum of the radiosignal occurs before the possible event Q3.

reflection from the satellite was registered in the spectrum. The selected filter V is transparent for this band. Therefore the flash of Europe registered through the filter V was probably tied with strong luminosity of the S^+ bands in the Jupiter atmosphere during its collision with the nucleus A.

The second flash was registered on July, 20 at $19^h32^m09^s$ in the course of observations with filter B and the same electrophotometer. Its moment differs from the predicted one of the fall of fragment Q2 by 12 min that exceeds twice the error of the predicted moment. Parameters of the flash: the outset of the outburst at $19^h32^m09^s$ UT, July 20, the duration of the outburst 2.7 sec, the amplitude 0.12 mag. This flash, in the authors' opinion, objectively reflects the outburst process in the Jupiter atmosphere that took place as a result of the impact at the registered moment of the invisible fragment Q3 (may be a dust cloud) of the nucleus of SL-9 comet. It is also possible that at that moment a dense cloud of gas and dust of the size of 200 km with the velocity 65 km/sec penetrated into the Jupiter atmosphere, which can explain a 3 sec duration of the flash. The proof of the flash being real is probably observations of radioemission of Jupiter on the 3.5-cm wave that were made by the group headed by Musatenko in Evpatoria with the 70-m radiotelescope (Musatenko *et at.*, 1995). The radiosignal is a good evidence of the fact that near the moment of the fall of Q3 there was a monotonous increase in radioemission on the 3.5 m wave from the planet. Almost exactly at the moment of the fall of Q3 there was a decrease in radioemission. The maximal deviation that characterized the decrease in Jupiter radioemission was observed at the moment of the event Q3 (Figure 2). This decrease was possibly connected with penetration of

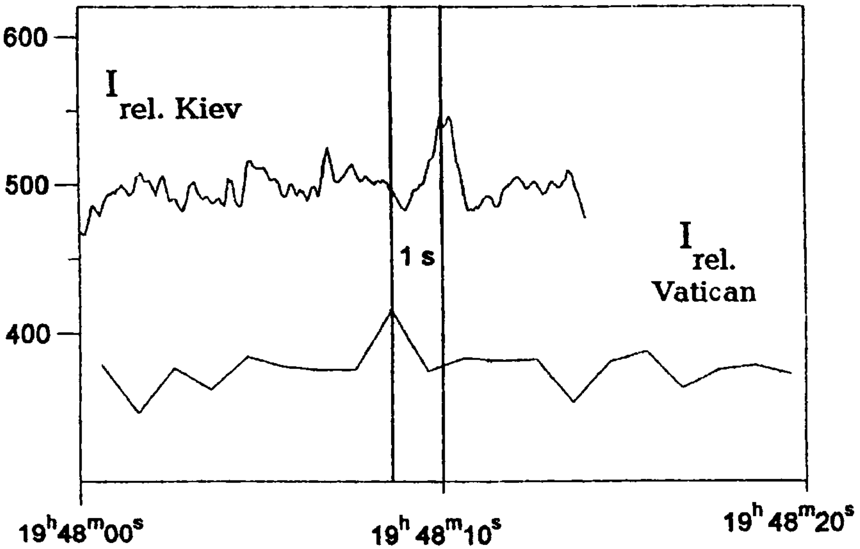

Figure 3 Comparison of the Kiev and Vatican photoelectric records of the brightness of Io at the time of the fragment Q2 fall.

large amounts of dust associated with the fragment Q3 that led to decrease in the radioemission of Jupiter.

The third flash in accordance with our observations took place on July, 20 at $19^h 48^m 10^s$ and was connected with the fall of the fragment Q2. The observed moment differs from the predicted one by ~ 4 minutes, which lies within the limits of the error of the theoretically calculated moment of the event Q2. This very flash obtained through observations made near Kiev was practically registered at the same moment by Italian astronomers Consolmagno and Menard at the Vatican observatory with the electrophotometer installed on the 0.6 m Cassegrain telescope. Taking in consideration that the time of records made by observers in Kiev and at Vatican is of the order 1 sec, we should acknowledge difference in the moments by 1 sec to be insignificant and lying in the limits of a temporal error of the moment observed at the two observatories. If the mean moment between these two observations is considered $19^h 48^m 09.5^s$ as the moment that should be acknowledged as real for the fall of the fragment Q2, then the observations made in Kiev differ by −0.5 sec while those made at Vatican by +0.5 sec. The authors consider it to be a remarkable coincidence of the Kiev and Vatican observations of the fragment Q2 fall on to Jupiter.

Figure 3 gives the Kiev and Vatican photoelectric records of the relative brightness of the Io satellite in which the 1 sec flashes of Io at the fall of the fragment Q2 are clearly seen. Besides coincidences in the times of the event Q2 coincidences of the registered amplitudes of the flash ~ 0.11 mag and its duration should be considered. Taking into consideration the afore said, we state that we have registered the real moment of the nucleus Q2 impact, i.e. July, 20 1994 at $19^h48^m09^s$ UT. This moment is to be taken into consideration by specialists in celestial mechanics when calculating the final orbits of the secondary nucleus Q2 of the comet SL-9 as well as when investigating its evolution in the past to clear up the origin of the comet SL-9.

One of the key problems of the unique event – collision of the comet SL-9 with Jupiter is a question of the origin of the comet. It is common knowledge that the comet was captured by Jupiter during an occasional encounter. On the other hand, there is well-known evidence of the presence of matter of cometary nature deep in the sphere of influence of the giant-planets, in the system of their satellites. The matter can be present in unstable orbits. There are systems of rings of the giant-planets. As is acknowledged today, these very satellites of the planets are sources for replenishment of these ring systems. Possibly, comets similar to the comet SL-9 are generated by satellites.

On July 26, 1983 in the course of observations of the Io appearance from behind the shadow of Jupiter the outburst with the 0.5 magnitude was observed on this satellite (Hammel and Nelson, 1993). In their paper Hammel and Nelson consider that the reason for this outburst was a reflection of light from the fireball in the Jupiter atmosphere at the moment of fall of a considerably heavy body on to it, as was in the case of the comet SL-9. As the observations showed, outbursts from the collision of the nuclei of the comet SL-9 with Jupiter happened to be significantly weaker. At the same time dark spots that had existed at least for a month were clearly observed on Jupiter's disc. If the outburst on Io (1983) is of a similar nature, then it is not clear why noticeable changes on Jupiter's disc have not been observed.

In our opinion, this particular outburst might be related to the explosion on Io itself, as a result of which the matter whose part was later observed as the comet SL-9, had been thrown off the Io surface. Here, the object thrown out might have been in the form of a jet that might have formed a chain of bodies which later was observed as a comet-train. Such a type of the comet origin can explain peculiarities of the comet composition, because the lines of Li and S were observed in the spectra of the spots, but the lines of typically comet emissions (CN, C_2, NH) were absent (Crovisier, 1995). The velocity of ejection could be not substantially greater than the escape velocity for Io (2.56 km/s). This is because the outburst was observable on the leading hemisphere of Io when the velocity of ejection is added up to the velocity of the orbital movement of Io. For calculation the initial ejection velocity is assumed to be equal to 3 km/s. The lower limit of the mass of the body thrown out could be calculated by the total mass of comet SL-9 fragments. We shall assume it equal to the mass of a spherical body with the 10 km diameter and the density of 0.3 g/cm^3 (1.6–10^{17} g). According to this data we can estimate the energy of the outburst assuming that 1% of the total energy is spent on the ejection of the matter off the Io surface into space. The outburst energy is 7×10^{29} erg.

Reasons for this outburst on Io might be as follows:

(1) Powerful eruption of one of the volcanoes. During the flight of the "Voyagers" (1979–1980) there were observed velocities up to 1 km/s (Strom *et al.*, 1981)

which are not substantially smaller than the escaping velocities from Io. Thus, it is quite permissible to assume that in the course of this powerful eruption there might be an ejection matter into the near space.

(2) According to the Drobyshevski hypothesis (Drobyshevski, 1994) ices on satellites of the giant planets are enriched by products of electrolysis and could explode either spontaneously or due to the fall of a meteorite on the satellite. According to his estimation the energy accumulated in the ices equals 2.3×10^{10} erg/g. In order to obtain the required energy it is sufficient for 2600 km^3 ices to explode.

(3) A combined mechanism when the fall of an asteroid or a comet might initiate explosive volcanic eruption.

In all these cases a new geological formation of a crater type or volcanic caldera will have to appear on the Io surface that will be possibly observed from board the spacecraft "Galileo" at the end of 1995.

4 CONCLUSION

On the basis of the time-resolved photometric observations of the Jupiter satellites three possible light echoes from fireballs in Jupiter's atmosphere were registered. (1) The A impact has the following parameters: filter V, the outset of the outburst at $20^h10^m38^s$ UT July, 16, the duration of the outburst 0.7 sec, the amplitude 0.16 mag. (2) Parameters of the Q3 impact: filter B, the outset of the outburst at $19^h32^m09^s$ UT July, 20, the duration of the outburst 2.7 sec, the amplitude 0.12 mag (3) Parameters of the Q2 impact: filter B, the outset at $19^h48^m10^s$ UT, the duration 1.0 sec, the amplitude 0.11 mag. This particular flash moment actually coincides with the analogous flash moment registered at the Vatican Observatory as well as it is close to the predicted flash moment. (4) In accordance with these flash amplitudes fragment radii are estimated: $R(A) = 1.42$ km for $\rho = 0.3\ g/cm^3$ (1.00 km for $\rho = 1$ g/cm^3); $R(Q3) = 0.96$ km for $\rho = 0.3$ g/cm^3 (0.64 km for $\rho = 1$ g/cm^3); $R(Q2) = 0.65$ km for $\rho = 0.3$ g/cm^3 (0.43 km for $\rho = 1$ g/cm^3). (5) A hypothesis concerning the origin of the comet SL-9 as a result of its throw off the Io surface in 1983 was advanced.

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