Metallic emission lines during the impacts L and Q_1 of comet P/Shoemaker Levy 9 in Jupiter

M. Roos-Serote, A. Barucci, J. Crovisier, P. Drossart, M. Fulchignoni, J. Lecacheux and F. Roques

Observatoire de Paris (Section de Meudon), France

Abstract. High resolution spectroscopy of the impacts and impact sites of comet P/Shoemaker-Levy 9 in Jupiter has been performed at the Pic-du-Midi observatory, France. The transient emission of seven emission lines from five different metals (Na, Fe, Ca, Li, K) and of the Hα line have been identified in spectra from the fresh impact sites of fragments L and Q_1.

Observations and Reduction

The French planetary science community observed the impact of comet P/Shoemaker-Levy 9 in Jupiter within a coordinated program, that included imaging, spectroscopy, photometry, etc. in as many as possible different wavelength regions (UV, visible, IR, radio). In this framework, this paper deals with spectroscopy at visible wavelengths carried out with the 2-meter Bernard Lyot telescope, equipped with the MUSICOS [*Baudrand and Bohm,* 1992] spectrograph, at the Pic-du-Midi observatory, France. The observations span the period from July 16^{th} to July 24^{th} 1994. The spectra were recorded by a Thomson CCD (1024x1024 pixels). The covered spectral range is $564< \lambda <875$ nm, with a spectral resolution of about 36000, and the spectrum is spread over 39 orders with little overlap or small gaps between the adjacent orders. The spectrograph is fed by a fiber of 50 μm diameter that corresponds to a field of view of 2.2″ (Jupiter's diameter measures about 38″). To point the fiber at the location of the impacts, positional data from the 1 meter telescope at Pic-du-Midi was continuously used [*Drossart et al., this issue*]. A guidance camera (no filter) allowed manual corrections during the integration. Due to the high capacity of the instrument and excellent meteorological conditions, the obtained spectra are of high quality.

The observations consist of:

(1) 35 spectra of the impact zones A, C, D, E, G, H, K, L, Q, S and W with an integration time of about 20 minutes each.

(2) bias, flat-field and calibration lamp spectra, which were secured before and after each observation session.

(3) spectra of the part of the planet at the central meridian at +45° latitude, to be used for absolute flux calibrations.

The spectra were reduced using special MUSICOS software [*Böhm,* 1993], following standard procedures that include: wavelength calibration, "flattening" of the data, collapsing the two dimensional spectra, then subtraction of the bias from the raw data, cosmic ray removal and finally absolute flux calibration. The SNR of the reduced spectra is of the order of 100 over the whole spectral range.

The absolute calibration was uncertain because stars cannot be used as calibrators for an extended source in this instrument. Due to the small aperture of the fiber, starlight is lost and flux measuments are thus uncertain. The reflectivity of the observed zone was determined by comparing with the spectrum from +45° latitude at the central meridian. The reflectivity of Jupiter at this latitude has been taken from *Orton* [1975], and the flux of the line has been measured using the surface of the line above the continuum. To take into account the continuum variation with wavelength at high spectral resolution, we have taken the relative spectral variation of the albedo of Jupiter from full disk measurements by *Karkoschka* [1994]. This procedure introduces uncertainties as large as 20% on the absolute flux measurement, in particular because of the different air masses on Earth between the reference spectra and those of the impact sites. However, relative fluxes are more accurate, since the uncertainties are then mainly due to the line surface measurement, which for strong lines, is of the order of the SNR.

Results

Observations were made at the time of impacts L and Q_1 and within one hour after them. These are the spectra which show strong metal emission lines (Table 1). In total, seven emission lines have been identified. Table 2 shows which lines were observed in which spectrum. Search and identification of other lines are still going on.

Figure 1 shows the evolution of the emission lines of the Na doublet (589 nm) during the L impact. The lines appear for the first time in the second spectrum of Figure 1, which is started 00:15:12 after the accepted impact time 22:16:48 [*Martin et al.,* 1994]. Comparing to spectra from *Walton et al.* [1994], which have a better time resolution, it appears that we stopped the integration of the first spectrum shown in Figure 1 just

Paper number 95GL00809
0094-8534/95/95GL-00809$03.00

Table 1. Observations of emission lines

No.	Date July 1994	Start Time (UT)	Exp. Time (s)	Impact Site	Remarks, Impact Times[a] (UT)
01	19	22:04:0	1500	L	22:16:48
02	19	22:32:0	1200	L	Emission
03	19	22:57:0	1200	L	Emission
04	20	19:45:0	1200	Q_2	19:44
05	20	20:14:0	1200	Q_1	20:13 Emission

[a] *Martin et al.* 1994

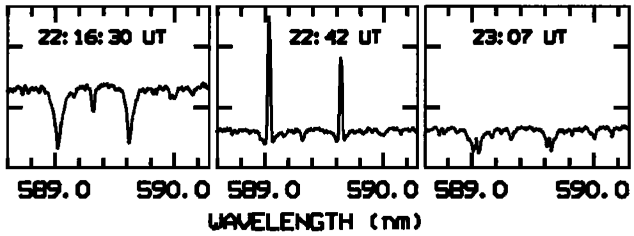

Figure 1. A time sequence showing the evolution of the Na emission lines during the L impact from spectra No. 01, 02 and 03 with (different !) integration times as given in Table 1. The times are indicated at the midpoint of the integration. The accepted impact times are 22:16:48 UT (19^{th} July), 19:44 UT and 20:13 UT (20^{th} July) for the impacts L, Q_2 and Q_1 respectively [*Martin et al.*, 1994]. As can be seen for impact L, emission is observed at least 16 minutes after the actual impact. The vertical scale is in arbitrary units. Table 2 gives the measured fluxes of the lines.

before (22:29 UT) the maximum of emission (22:30:55 UT), and that we started the integration of the second spectrum just after (22:32 UT) this maximum.

In the third spectrum, started at 22:57 UT (00:40 after the impact) there is still some emission, but it is now comparable to the continuum level. Later, any signature of emission disappeared. The same type of evolution has been observed for the other metal emission lines (Table 2). In Table 2, column 6, we list the flux measurements of the lines, which are related to the area of the line above the continuum. We remark that the fluxes for the K line are rather uncertain, because the continuum in this region is strongly disturbed by telluric O_2 absorption. The fact that we see only the 766.50 nm line of the K doublet is because the other one (769.89 nm) falls into a spectral gap between two adjacent orders.

Not included in Table 2 is the Hα line at 656.3 nm. Its emission is much smaller than the Hα absorption in the reflected solar spectrum, but the change in the absorption feature is clearly visible when divided by a spectrum without emissions.

In Figure 2 all seven identified metal emission lines seen in spectrum 02 (Table 1, Impact L) are shown. The figure represents a division of spectrum 02 by spectrum 01, which does not show any emission at all.

Table 2. Identification of the emission lines of L and Q_1

No.		Identification[a]	λ_{theory}[b] nm	$\lambda_{corrected}$[c] nm	FWHM[d] nm	Flux 10^{-16} Wm^{-2}
02	Na I	$3s\ ^2S - 3p\ ^2P^0\ J\frac{1}{2} - \frac{3}{2}$	589.00	589.00	0.024	5.5
02	Na I	$3s\ ^2S - 3p\ ^2P^0\ J\frac{1}{2} - \frac{1}{2}$	589.59	589.60	0.025	3.6
02	Fe I	$a\ ^5F - z\ ^7F^0\ J5 - 6$	635.87	635.88	0.054	0.2
02	Ca I	$4s^2\ ^1S - 4p\ ^3P^0$	657.28	657.28	0.026	8.2
02	Li I	$2s\ ^2S - 2p\ ^2P^0$	670.78	670.79	0.033	1.2
02	K I	$4s\ ^2S - 4p\ ^2P^0\ J\frac{1}{2} - \frac{3}{2}$	766.49	766.50	0.041	7.5[e]
02	Fe I	$a\ ^5F - z\ ^7D^0\ J5 - 5$	804.76	804.79	0.033	1.0
03	Na I	$3s\ ^2S - 3p\ ^2P^0\ J\frac{1}{2} - \frac{3}{2}$	589.00	589.00	0.019	0.4
03	Na I	$3s\ ^2S - 3p\ ^2P^0\ J\frac{1}{2} - \frac{1}{2}$	589.59	589.60	0.025	0.3
03	Fe I	$a\ ^5F - z\ ^7F^0\ J5 - 6$	635.87	635.88	0.006	0.1
03	Li I	$2s\ ^2S - 2p\ ^2P^0$	670.78	670.79	0.018	0.3
05	Na I	$3s\ ^2S - 3p\ ^2P^0\ J\frac{1}{2} - \frac{3}{2}$	589.00	589.00	0.061	1.3
05	Na I	$3s\ ^2S - 3p\ ^2P^0\ J\frac{1}{2} - \frac{1}{2}$	589.59	589.61	0.058	0.6
05	K I	$4s\ ^2S - 4p\ ^2P^0\ J\frac{1}{2} - \frac{3}{2}$	766.49	766.51	0.055	1.5[e]

[a] All are transitions from the ground state, except for both Fe I lines.
[b] In air, *Morton* 1991 (Na, Ca, Li, K) and *Nave et al.* 1994 (Fe)
[c] Doppler shift correction ~ -0.034 nm at 589 nm and ~ -0.046 nm at 804 nm.
[d] FWHM of the line when fitted by a gaussian
[e] The K I line is blended by telluric O_2 absorption lines, which precludes an accurate determination of the flux.

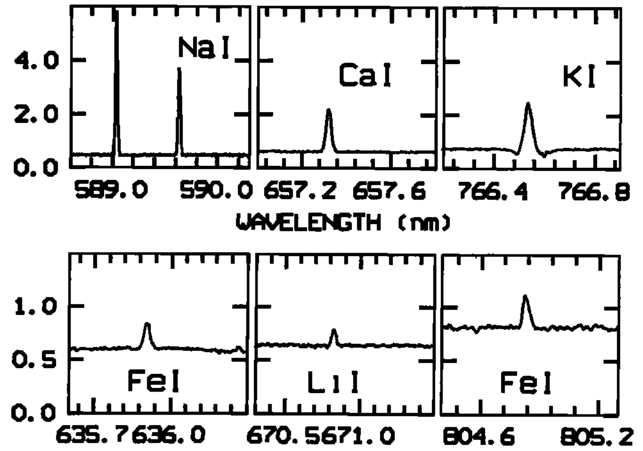

Figure 2. All 7 identified lines in the spectrum of impact L (No. 02 Table 1), that starts at 22:32 UT (00:15 after the actually accepted impact time, 22:16:48 UT [*Martin et al.*, 1994]). The vertical scale is in relative units, which is the result of a division with the spectrum just before the impact where no emission lines are observed (No. 01 Table 1). The uneven continuum for the K line (c) is due to strong telluric O_2 absorption in that region. Table 2 gives the measured fluxes of the strongest lines.

Discussion: the Emission Lines

Atomic metals or metallic compounds are normally not present in Jupiter's atmosphere. Therefore, we conclude the metals observed during the impact L and Q_1 were released from cometary refractory material. Before the Shoemaker-Levy 9 event, such atomic lines were only observed in spectra from cometary material in meteor fireballs [*Borovička*, 1993, 1994] and in sun-grazing comets. The best documented case is that of Comet Ikeya-Seki 1965 VIII which approached the Sun to only 0.0078 AU (*i.e.* within the corona) on October 21, 1965. Lines of several metal atoms (Na, K, Ca, Ca^+, V, Cr, Mn, Fe, Co, Ni, Cu,) were observed at that moment, and the retrieval of relative abundances was possible [*Preston*, 1967; *Arpigny*, 1979]. The Li resonant line could not be detected.

Na resonant lines were also observed in several comets that passed the Sun at less than 1 AU. The elemental composition of comet Halley's dust, including metals up to nickel, was also investigated by in situ mass spectroscopy aboard the *VEGA* and *Giotto* space probes [*Jessberger et al.*, 1988]. Abundancies close to solar were found for elements from carbon to nickel. Again, Li was not observed.

Various mechanisms might be responsible for the emission of atomic lines in the plumes of the SL–9 impacts. Their understanding is a requisite in order to interpret the observed line intensities and to retrieve abundances. We have to explain the emissions, with comparable intensities, of allowed lines (Na, K, Li), for which Einstein coefficients A_{ij} are of the order of several 10^7 s^{-1}, and of almost forbidden lines (Ca, Fe) coupling states with different multiplicities with A_{ij} of the order of 10^3 s^{-1} only. Three mechanisms are proposed, not excluding others or combinations of mechanisms:

(i) Resonant fluorescence is a well-known mechanism responsible for the emission of most atomic lines and molecular bands in comets. It is also known to be the mechanism of sodium emission in Io's torus. The radial heliocentric velocity is a critical parameter, since the same resonant lines (for Na and K) are present as strong absorptions in the solar spectrum, so that the number of photons available to exite these atoms is a strong function of wavelength. The emission rates for resonant fluorescence at Jupiter's limb (assuming an heliocentric velocity of 8 km s^{-1}) are typically $g \simeq 10^{-1}$ photons s^{-1} per atom for Na, Li or K, but only $\simeq 10^{-5}$ s^{-1} for Ca or Fe. The velocity of the ejected material on the ballistic trajectories has been neglegted, because most of our observations took place more than half an hour after the impact, when most of the material has already fallen back into the jovian atmosphere, according to HST plume observations [*Hammel et al.*, 1994].

(ii) The lines we observed might be significantly excited by thermal collisions if the temperature in the plume is high enough ($T \simeq 1000$ to 1500 K). However, the collision rate in the plume is probably too low to ensure an efficient thermal emission rate of the lines.

(iii) Chemical reactions or electronic recombination [*Pacheco, private communication*] might be responsible for the excitation of atoms in metastable states followed by the emission of forbidden transitions (prompt emission).

The intensity ratio of the Na doublet lines is expected to be [5896]/[5890] = 1.2 for the fluorescence mechanism and 1 for the thermal mechanism in an optically thick situation. In the optically thin case, these numbers are 0.61 and 0.5 respectively. The observed intensity ratio is $\simeq 0.66$ for the L plume spectrum (No. 02 Table 1) and $\simeq 0.50$ for the Q_1 plume spectrum (No. 05 Table 1). This suggests that the lines were not optically thick, but it does not allow to discriminate between possible mechanisms.

The timing of the observations of the L event can also help to determine the origin of the emissions by giving some constraints on the interpretation. The first spectrum that shows emission starts at 22:32 UT, (00:15 after impact). According to geometry calculations for impact L [*Drossart et al., this issue*], this time corresponds closely to the passage of the impact site over the limb (22:29:33 UT $\pm$ 1 minute) as seen from Earth. At that time, the impact site is still in the shadow, *i.e* it is still behind the limb as seen from the Sun, and the minimum distance to the shadow border is about 450 km above the 1 mbar level. Fluorescence due to solar illumination could occur in the cloud ejected at ballistic altitudes, that has been seen in HST images [*Hammel et al.*, 1994], but this cloud, for impact L, should reach its maximum altitude ($z \sim 3600$ km) at 22h:26m UT, *i.e* before the maximum of emission in Na near 22:31 UT, as seen by [*Walton et al.*, 1994], in agreement with our timing. Therefore, geometrical considerations seem to favor an emission coming from the atmosphere of

Jupiter, that crosses the limb at the time of the maximum emission. The rapid decrease of the emissions could then correspond to the rapid cooling of the hot gas, which is comparable to the cooling time observed in methane emissions [*Encrenaz et al., this issue*; *Maillard et al., this issue*]. Nevertheless, thermal emission is inconsistent with Ca line emissions, and there might be a combination of several mechanisms at work.

We note that emission lines were not seen in other spectra then in those mentioned in Table 1. This suggests that the metallic emission lines were observed only within one hour after the impacts; their fading might be explained by either chemical reactions (like the formation of hydrures), a sedimentation of the metals in the collisional layer of the atmosphere, or to a temperature decrease if thermal excitation is involved.

All these issues could probably only be solved in the future by considering all atomic lines observed by different instruments at various wavelengths [*Noll et al.*, 1994; *Prangé et al.*, 1994; *Walton et al.*, 1994].

Acknowledgments. We thank the staff at the Pic–du-Midi observatory for their expertise and adequate assistance during the observations. We also thank B. Foing and C. Catala for their help during the observations and the reduction of the MUSICOS data. And we are greatful to Margarida Serote Roos for her great help and instructions in how to use MIDAS software.

References

Arpigny, C., Relative abundances of the heavy elements in comet Ikeya-Seki (1965 VIII), *Mem. Soc. Roy. Liège*, *22*, 189, 1979.

Baudrand, J., and T. Bohm, MUSICOS: a fiber-fed spectrograph for multi-sit observations. *Astron. Astrophys.*, *259*, 711, 1992.

Böhm, T., Phénomènes actifs dans les étoiles pré-séquence principale de masse intermédiaire (Ae/Be de Herbig), *Thesis*, Paris, 1993.

Borovička, J., A fireball spectrum analysis, *Astron. Astrophys.*, *279*, 627, 1993.

Borovička, J., Line identifications in a fireball spectrum, *Astron. Astrophys.*, Supp., *103*, 83, 1994.

Hammel, H.B., T.E. Dowling, J. Harrington, J.R. Mills, R.F. Beebe, A.A. Simon, L.F. Huber, A.P. Ingersoll, A. Toigo, G.S. Orton, R.A. West, E. De Jong, E. Karkoschka, and D.M. Kuehn, HST imaging of Jupiter's atmosphere in July 1994: dynamical effects from the impact of Comet P/Shoemaker–Levy 9, *Bull. Amer. Astron. Soc.*, *26*, 1565, 1994

Jessberger, E.K., A. Christoforidis, and J. Kissel, Aspects of the major element composition of Halley's dust, *Nature*, *332*, 691, 1988.

Karkoschka, E., Spectrophotometry of the Jovian planets and Titan at 300– to 1000– nm wavelength: the methane spectrum, *Icarus*, *111*, 174, 1994.

Martin, T.Z., L. Tamppari, G.S. Orton, I. Claypool, and L. Travis, Galileo PPR observations of Shoemaker–Levy 9, *Bull. Amer. Astron. Soc.* , *26*, 1566, 1994

Morton, D.C., Atomic data resonance lines. I. Wavelenghts longward of the Lyman limit, *Astrophys. J.* Supp., *77*, 119, 1991.

Nave, G., S. Johansson, R.C.M. Learner, A.P.Thorne and J.W. Brault, A new multiplet table for Fe , *Astrophys. J.* Supp., *94*, 221, 1994.

Noll, K.S., M.A. McGrath, L.M. Trafton, S.K. Atreya, J.J. Caldwell, H.A.Weaver, R.V. Yelle, C. Barnet and S. Edgington, Hubble Space Telescope spectrometric observations of Jupiter after the collision of comet P/Shoemaker–Levy 9, *submitted to Science*, 1994.

Orton, G.S., Spatially resolved absolute spectral reflectivity of Jupiter: 3390-8400 Å, *Icarus*, *26*, 159, 1975.

Prangé, R., C. Emerich, A. Talavera, W. Harris, G. Ballester, M.Combi, T.Livengood and M. McGrath, Jupiter and comet 1993e, *IAU Circ., No. 6041*, 1994.

Preston, G.W, The spectrum of comet Ikeya-Seki (1965f), *Astrophys. J.*, *147*, 718, 1967.

Walton, N., R. Catchpole, and S. Ramsay, The Shoemaker-Levy 9 Jupiter collision, *Spectrum*, *3*, 4; Also *IAU Circ., No. 6033*, 1994.

M. Roos–Serote, A. Barucci, J. Crovisier, P. Drossart, M. Fulchignoni, J. Lecacheux and F. Roques, Observatoire de Paris (Section de Meudon), 5 Place Jules Janssen, 92195 Meudon CEDEX, France

(received December 7, 1994; revised February 2, 1995; accepted February 13, 1995.)