# The SL-9 Workshop Round-Table Discussion – A Summary

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## Introduction

(by R. West, ESO-Garching)

The SL-9 Workshop at ESO-Garching, demonstrated that – since the exciting impact week from July 16 to 22, 1994, over the IAU General Assembly in The Hague in late August 1994 and the DPS Meeting in Washington DC in early November 1994 – significant progress has been achieved in the understanding of the SL-9 phenomena. The fragmentation of the object, the initial impact phenomena, their spectral signatures and long-term effects of the spots in Jupiter's atmosphere can now be analysed on the basis of the available flux- and time-calibrated observations over a wide wavelength range covering X-ray, UV, visual, IR to radio regions. Simultaneously and to a large extent driven by expected and unexpected observational results, the interpretation and theoretical modelling of the SL-9 pre- and post-impact phenomena have brought up new scenarios and already very valuable quantitative descriptions for various phases of the SL-9 event. However, we are still far away from a global scenario and satisfactory understanding of all phenomena related to the SL-9 impacts at Jupiter. This holds equally for observation and theory. Statements of workshop participants like (cited anonymously):

– "Something" exploding in the atmosphere . . .

– We see different effects at different times at different wavelengths!

– I don't see it either, but I did observe it!

– There is perfect agreement, except that in our images the northern hemisphere is bright, in his data it is in the south!

– I think everybody will finish publishing the observations this year (big smiles . . .)!

– I did expect some questions! may reflect the vivid discussions of the still puzzling results obtained so far from a unique and tremendous amount of data gathered all over the world.

This round-table discussion at the end of the workshop aims for conclusions on what is really understood and which steps into which directions are now required to proceed towards a final clarification of the SL-9 impacts at Jupiter.

## Fragment Size (by H. Rickman, Astronomical Observatory, Uppsala)

The capture of SL-9 by Jupiter may well remain obscured since the backward orbit integration based upon the available astrometric data can probably not be very significantly improved. However, there are essentially two potential sources from which SL-9 could have come from, i.e. the Trojan zone in the Jupiter sphere of influence and a low velocity accretion zone of cometary objects outside Jupiter's sphere of influence. The mechanical strength of the object was low (probably of the order of 100 Pa). Trojan objects as SL-9 pre-capture candidates are therefore unlikely since they are not believed to be that fragile. Therefore, SL-9 may have resembled more an aggregate of only weakly bound cometary nuclei. The tidal splitting of SL-9 points to a relatively low tensile strength, in that way also imposing a constraint on the radius for the parent body. A fragment size of about 1 km would fit the existing observations.

### *Discussion*

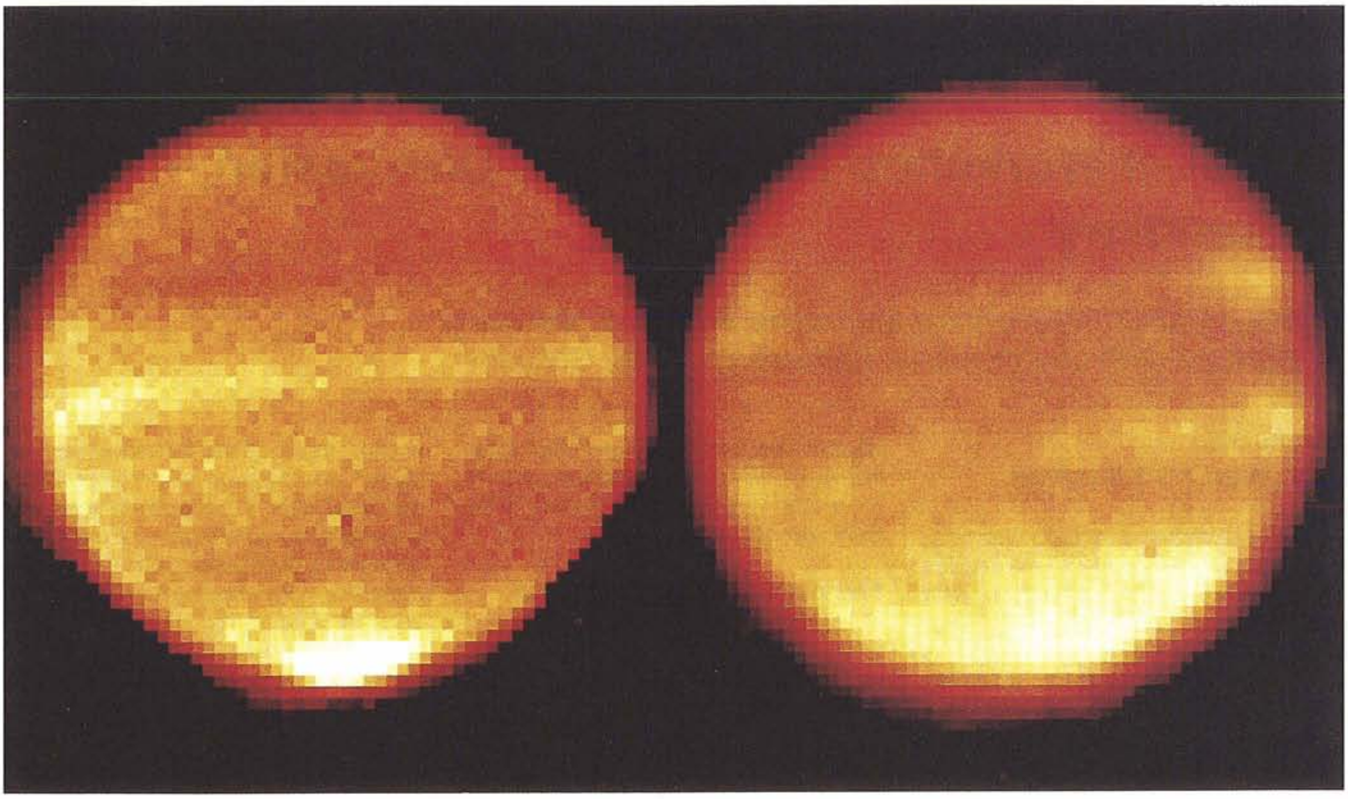
Corrections to the formula for tidal disruption should be made since object rotation and adhesive forces of the body material are not included in the model (Shulman). Gravitational pressure was also neglected so far which would support larger radii for the parent object of the fragmented nuclei. SL-9 may be considered as loose aggregate of planetesimals which split in Jupiter's orbit along weakest adhesive walls (Kelemen). For equal tensile strengths a big comet is easier to break (Sekanina).

## Penetration Depths (by B. Mosser, Institut d'Astrophysique, Paris)

The actual penetration depth of the SL-9 fragments into the Jovian atmosphere is still an open question. The proposed scenarios range from "far above the cloud layers", over "right on top or slightly below the upper layer" to penetration "down into atmospheric levels of several bars". The penetration depth should be related to the size of the body entering the atmosphere, i.e., the larger the size of the fragment, the deeper the penetration into the atmosphere of Jupiter. However, a direct relation between these still unknown quantities has not yet been demonstrated. A key role for the description of the entry phenomena is played by the energy deposition in the atmosphere versus altitude, a relation which has so far not been established. Besides the lightcurve features of the impacts and post-impact seismic phenomena on Jupiter, the chemical abundances in the ejecta clouds may also allow to constrain the entry depth of the fragments.

### *Discussion*

Mass ablation plays a dominant role for meteorites entering the atmosphere of Earth (for instance: a 50-ton meteorite was observed to be totally dissipated, already above an altitude of 55 km in the Earth's atmosphere). Such a scenario for the SL-9 entry at Jupiter would imply a much stronger mass loss and kinetic energy dissipation of the fragments above the upper cloud layers with even complete disintegration at pressure levels of some mbar (Sekanina). Whether the existing smart theory for meteorite entries on Earth can be applied to the description of the SL-9 impact at Jupiter, remains an open issue for the future. However, for our ongoing analysis of the SL-9 impacts it seems absolutely necessary to invoke also the knowledge about meteorite phenomena on Earth (Shulman). This may be improved for the entry of larger bodies with a weaker and differentiated internal structure (Mosser). The possibility of constraining the fragments' penetration depth by the non-detection of explosion signals at 5 mm (Käufl) was questioned (Orton, Hammel), since it is not clear that this wavelength range is really sensing the 5 bar level in the Jovian at-



## *Persistent Effects of SL-9 Impacts On Jupiter*

*These two images illustrate the persistent effects of the impacts of the fragments of Comet Shoemaker-Levy 9 on Jupiter which took place on July 16–22, 1994. The first was obtained 5 months before these impacts; the second almost 7 months thereafter. Both were taken with the TIMMI instrument attached to the ESO 3.6-m telescope at La Silla. The first image was taken in the night February 28–March 1, 1994 by ESO observers Ted Kostiuk, Tim Livengood and Hans Ulrich Käufl as part of a parallel observation of Jupiter together with the IUE spacecraft to study auroral phenomena on Jupiter. It shows a bright spot at the south pole. This is the well-known phenomenon of the Southern Aurora which was the main objective of this observation run. While on Earth the Aurora Borealis is a transient effect, it is nearly always present on Jupiter. Due to the inclination of Jupiter's magnetic axis, the appearance of this aurora depends on the rotational state of the planet.*

*The second image was taken on February 5, 1995, at 14 h 20 UT, i.e. in daytime at La Silla, at a moment when this aurora was located on the rear side of Jupiter and therefore not visible. When compared to the first image, it is obvious that the entire southern hemisphere southwards of –40 degree (which includes the SL-9 impact zones) now appears brighter than one year before. This image therefore indicates that debris (e.g. fine dust) from the impacts is still present in the upper atmosphere. Here it absorbs the sunlight and causes an extra heating effect; we see this in this image as thermal emission from the methane molecules there. Apparently the dust from the individual impact sites has now been mixed rather uniformly throughout the southern polar region.*

*Technical information: Both images are aligned so that the Jupiter North Pole is up and astronomical east to the left. Both images have been made with 0.45 arcsec/pixel magnification; however, because of the different apparition (the Jupiter–Earth distance in February 1995 is 5.75 AU versus ~ 4.95 in February 1994), this corresponds to 1900 and 1620 km per pixel, respectively. Both images were taken with a filter sensitive to methane ($CH_4$) in the stratosphere of Jupiter having a wavelength pass band of 7.53–7.87 micron. Thermal emission of $CH_4$ in this band is known to be a good indicator of temperature in the stratosphere.*

mosphere. If the fragments did not penetrate deep into the sulphur clouds of Jupiter, they must have had a size of 4 km to explain the large amount of detected $S_2$ as being of cometary origin (A'Hearn).

### Lightcurves, Timing

(by G. Orton, JPL, Pasadena)

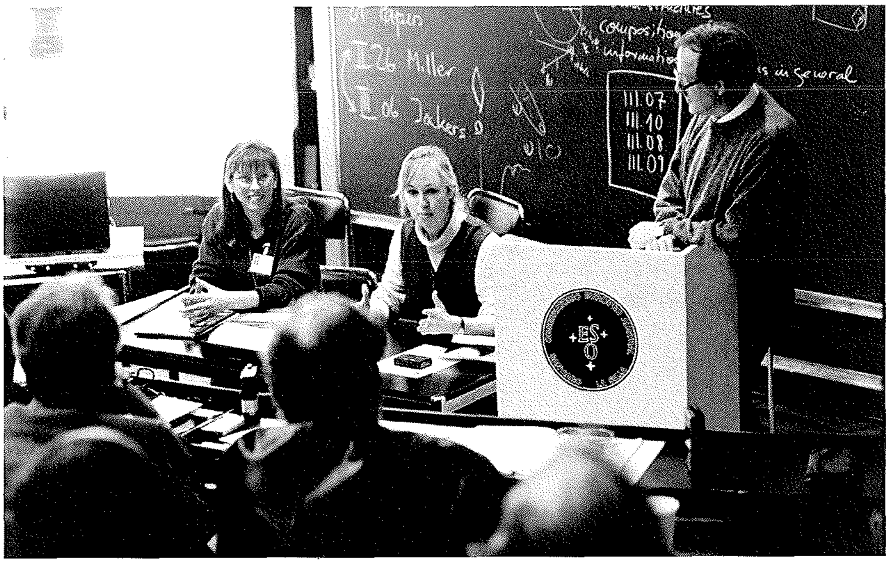
The impact lightcurves of the individual fragments are very similar at same wavelength, but exhibit interesting differences (for instance shoulders in the lightcurve decay phase) in the various wavelength ranges observed. There were signals recorded on the ground for almost all impacts which precede the first Galileo detections. Which phenomena have we seen in these first precursors? Can we develop a "standard impact model" and can this include chemistry?

A central question of the SL-9 phenomena is the calibration of the impact energy and the partitioning of the deposited energy in the various dissipative channels in the atmosphere. Related to this are further similarities like the almost identical plume height and the very similar albedo of the fresh impact particulates. However, the plumes behave different in their morphology, size of the impact region and lifetime of the particulates as well as the temperature variations in the stratosphere and troposphere. The basic question is: what can we use for calibration, or in other words, whas it always the same for different fragments?

Another important point is the partitioning of the energy in the atmosphere and the determination of the temperature variations/gradients between the stratosphere and the troposphere. We have to understand the lightcurves and model them. All of this can only be accomplished by collaborations between the observers of the different phenomena: 1. heating of the channel (IR), 2. bolide, 3. plume.

#### *Discussion*

A possible consent of this workshop on what was happening during the impact was formulated by H. Hammel: entry channel heating for the first precursor, a very hot fireball for the second precursor, followed by a rapid sweeping through of



*SL-9 Press Conference. From left to right: Heidi B. Hammel, Victoria Meadows, R. West.*

maximum light from UV to IR, but still increasing in luminosity. Time scale differences may also depend on the actual depths of the impact explosion (Hamilton).

**Shock Chemistry**
(by R. West, ESO-Garching)

The chemistry of the impact phenomena is even more complicated than their temporal evolution. Although a whole suite of post-impact ingredients was measured at the impact sites, we are very far from understanding what is ob-served. We do not know the composition and chemistry of the fireballs and plumes, and we have only preliminary ideas about the detailed causes for the very rapid changes that have been spectrally docu-mented. The simple picture of evaporat-ing gas of cometary origin does not easily match the observed phenomena. It is very evident that all of this requires proper theoretical treatment by experts who usually work outside the field of astronomy. Interdisciplinary collaborations are now needed and must be widely encouraged.

**Aeronomical Effects**
(by W.-H. Ip, MPI for Aeronomy, Katlenburg-Lindau)

The impact explosions caused disturbances in the atmosphere followed by disturbances of the Jovian ionosphere. The latter do couple back to atmospheric layers, in that way closing a loop which may play an important role for the understanding of the post-impact phenomena. There are also severe magnetospheric effects from the impacts which still await explanations: the $H_3^+$emission in the impact counterparts at northern latitudes, the brightening and dimming of the northern and southern aurorae and the injection and storage mechanisms for the synchrotron radiation observed. A very puzzling issue are the very selective effects on the inner and outer region of the Jovian magnetosphere whereas at the same time no reaction in the plasma torus of Io could be measured. The aeronomical effects observed call for a 2D theoretical treatment, or even 3D tomographic approach for solution.

*Discussion*

The phenomenological description of the impact effects to the Jovian magnetosphere is still incomplete since the VLA measurements are not yet available (Dulk). The amount of impact energy coupled into ionospheric and magnetospheric phenomena should comprise – to about 2 orders of magnitude – that of the X-ray and UV energy release by the phenomena (Ip). It is very unclear how the increase of synchrotron radio emission by Jupiter can be explained since it is in total contradiction to what was expected, i.e., a decrease of the radio emission due to electron absorption by the impact dust after migration into the magnetosphere. At the same time decametric observations do not show an increase in radio emission; so far, this has no reasonable physical interpretation (Miller, Dulk).

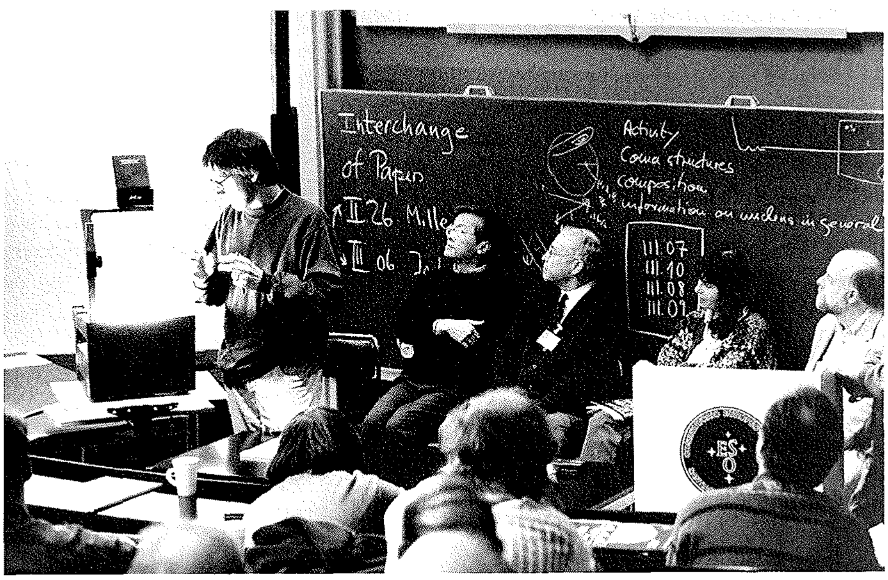
**Collaboration and Coordination**
(by T. Encrenaz, Observatoire de Paris-Meudon)

Since calibrated lightcurves and spectra of the impacts are available now from various sites in different wavelength ranges, it is very valuable and absolutely necessary that collaborations between the various groups start immediately. The synergy of multi-wavelength interpretations is now required to further the understanding of the impact phenomena. A very preliminary and still incomplete list of potential collaborations between groups of observers is compiled in Table 1 (sorted by impacts for the lightcurves and by wavelength range for spectral features).

It seems to be very important to compare the similarities and diversities between the detections of the same impacts.

*Discussion*

A more complete list of groups which have collected observations of the same



*SL-9 Round Table. From left to right: B. Mosser, W. H. Ip, H. Rickman, Th. Encrenaz, G. Orton.*

*TABLE 1. Lightcurves.*

| Fragment | Visible | Near-IR | Thermal IR |
|---|---|---|---|
| A | HST | Pic-du-Midi<br>Calar Alto<br>UKIRT | ESO<br>La Palma |
| C | | UKIRT<br>AAT<br>Japan<br>IRTF | |
| D | | AAT | |
| E | HST | Pic-du-Midi<br>Calar Alto | La Palma |
| G | HST | NIMS<br>IRTF<br>AAT | |
| H | PPR | Calar Alto<br>Pic-du-Midi<br>ESO | ESO<br>La Palma |
| K | SSI | AAT<br>Japan | |
| L | PPR | Pic-du-Midi<br>Calar Alto | La Palma |
| N | SSI | AAT | |
| Q | | Pic-du-Midi<br>Calar Alto | La Palma |
| R | | Keck<br>Palomar<br>NIMS<br>AAT | IRTF |
| S | | Pic-du-Midi<br>Calar Alto | |
| W | HST<br>SSI | AAT | |

*TABLE 2. Spectral identifications*

| Wavelength | Species | Group | Fragments |
|---|---|---|---|
| UV | $S_2$, S, SII, Na(*), Mg,<br>CS(*), $CS_2$, NH (*) | HST<br>IUE | |
| Visible | Na(*), Ca, Fe, Mg, Mn,<br>Li, K, H, Ha | La Palma<br>Pic-du-Midi | L, Q |
| 2.2–2.4 μm | $H_2$<br><br>CO(*)<br><br>$CH_4$(*)<br>$NH_3$(*)<br>$H_2O$ ? (*) | AAT<br>ESO<br>Calar Alto<br>AAT<br>AAT<br>AAT<br>AAT | C, D<br>A, E<br>H, L<br>C, D, G, K, R<br>C, D, G, K, R<br>C, D, G, K, R<br>C, D, G, K, R |
| 2.7–3.2 μm | O-H, C-H (*) | NIMS | G |
| 3.5 μm | $H_3^+$<br><br><br>$CH_4$(*) | ESO<br>UKIRT<br><br>ESO<br>UKIRT<br>CFHT | 1 week<br>after<br>impact<br>H<br>C<br>C, R |
| 4.7 μm | CO(*) | CFHT<br>IRTF | L<br>L |
| 7 μm | $H_2O$(*) | KAO | |
| 10 μm | $NH_3$(*)<br>$C_2H_4$ | IRTF<br>IRTF | G<br>G |
| mm | CO(*)<br><br>CS(*), OCS<br>HCN | IRAM<br>SEST<br>IRAM<br>JCMT | |
| cm | $H_2O$ ? (*) | Medicina | E |
| Multi-wavelength detection of species is indicated by symbol (*) | | | |

These preliminary tables were mainly compiled from the presentations of the workshop; many other data, US in particular, will probably be missing.

event shall be compiled within the next few weeks and will be attached to the proceedings of this workshop. Input for this list should be directed via e-mail, either to R. West (rwest@eso.org) or to M. A'Hearn (ma@astro.umd.edu).

Early speculations of the formation of a new ring around Jupiter due to dust ejected from the impactors during their decent are not very realistic, since most dust of SL-9 (at least down to 100 μm grains) hit Jupiter. Therefore, if something will happen to the ring, it should show only small effects (Hamilton).

It must be assumed that the impactors were totally evaporated during the explosions. New dust was formed in the impact plume within 2 to 3 minutes, but how and why is completely unclear. Whether there is a chemical differentiation in the dust, is also on open issue which can at present not be answered by the modellers (Fitzsimmons).

The most important question of the SL-9 impacts however is: *where did all that energy go?* (A'Hearn). Energy dissipation by shock breaking and ablation of the nuclei during entry into the Jovian atmosphere followed by increased deceleration during descent was so far not taken into account. Differential effects of that kind may have caused substructure in the lightcurves of the fragment impacts (Sekanina).

## Closing Remarks
(by R. West, ESO-Garching):

The three days of this workshop convincingly proved that considerable progress has been achieved in the compilation of reliable and quantitative observational facts, as well as in their theoretical understanding. It is nevertheless clear that we must continue the series of SL-9 conferences in order to improve the description of this unique event and before we may finally converge towards a comprehensive model of all related phenomena of the impacts at Jupiter. The next SL-9 conference is scheduled for 9–12 May 1995 in Baltimore. I am sure that later follow-up meetings are also very likely to occur, perhaps already in late 1995, and certainly next year.

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