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 16 to 22 July 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 of 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 keyrole 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 tons 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 on-going 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 μm (Käufl) was questioned (Orton, Hammel), since it is not clear that this wavelength range is really sensing the 5 bar level in the Jovian atmosphere. 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, what is 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 consense 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 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 observed. 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 documented. The simple picture of evaporating 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 multiwavelength 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 below (sorted by impacts for the lightcurves and by wavelength range for spectral features):

Table 1: Lightcurves

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

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 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 email, 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).

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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).

Table 2: Spectral identifications

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

Multiwavelength detection of species is indicated by symbol (*)

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.