COMETS AND
THE SOLAR SYSTEM

THE IMPACT OF COMET D/SHOEMAKER-LEVY 9 WITH JUPITER

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Abstract. The collision of comet D/Shoemaker-Levy 9 with Jupiter in July 1994 was an unprecedented opportunity to witness a phenomenon that was ubiquitous in the early solar system and which continues to shape its evolution. The tidal breakup of the comet, and the subsequent evolution of its fragments, have provided important insights into the nature of cometary nuclei, although conclusions regarding the comet's fundamental properties remain controversial. Detailed models describing the passage of the fragments through the jovian atmosphere have been fairly successful in explaining many aspects of the observations, including the appearance of giant plumes extending >3000 km above Jupiter's limb, the huge infrared signals following the splashback of material into the jovian atmosphere, and the formation of dark impact scars over large regions at mid-southern jovian latitudes. New chemical species (e.g., CO, H_2O, S_2, CS_2, CS, OCS, HCN, C_2H_4, and possibly H_2S) were created in Jupiter's atmosphere due to the shock heating of the mixture of cometary and jovian gases. The large NH_3 enhancement in the jovian stratosphere was apparently caused by heating of the ambient NH_3 cloud followed by upwelling. The presence of metal atoms and ions in the jovian atmosphere was an unmistakable signature of the comet. Photochemistry may have played an important role in the temporal evolution of the newly-created species. The appearance of expanding rings emanating from the impact sites was originally explained as the propagation of gravity waves, but this required an oxygen abundance in the deep jovian atmosphere that was $\sim$10 times solar, an hypothesis that has been apparently contradicted by recent results from the *Galileo* probe. Although the impacts clearly produced dramatic effects in Jupiter's atmosphere, most traces of the trauma were barely discernible one year later.

E. F. van Dishoeck (ed.), Molecules in Astrophysics: Probes and Processes, 205–218.

1. Introduction

Within three months of the discovery of comet D/Shoemaker-Levy 9 (hereafter referred to as "SL9") by the famous comet-hunting team in March of 1993 (Shoemaker et al., 1993), dynamical calculations demonstrated that this object had been captured by Jupiter and would likely impact the planet in July 1994 (Nakano & Marsden, 1993). From the cratering record on the planets and their satellites, we have long known that similar impacts have shaped the evolution of our solar system, including the strong possibility that a large asteroid or comet impacting the Earth contributed to the extinction of the dinosaurs ~65 million years ago. The collision of SL9 with Jupiter offered a unique opportunity to make a detailed study of the interaction of a comet with a planetary atmosphere. Fortunately, nature provided over a year of advance notice of the impending event, so that most observatories would be ready to record whatever transpired. In addition, the *Galileo* spacecraft was closing in on its rendezvous with Jupiter and would have a direct view of the explosions.

In this paper we review what has been learned from the SL9-Jupiter impacts almost exactly two years after the event. In section 2 we discuss the comet itself: its dynamical history, its tidal disruption, and the clues relating to the size, structure, composition, and activity of the nucleus. In section 3 we describe what happened during the passage of the cometary fragments through the jovian atmosphere, primarily as discerned from the interpretation of infrared lightcurves. Following the collisions, a remarkably diverse suite of molecules were observed in Jupiter's atmosphere, which are normally not present in detectable abundances. In section 4 we discuss which molecules were created, how they may have been created, and their temporal evolution. Finally, in the last section we summarize which results from the SL9-Jupiter observing campaign are robust and identify areas where further work is needed.

This paper is necessarily very short and topical. For a much more comprehensive review of the many SL9-Jupiter investigations, the reader is referred to the book recently published by Cambridge University Press (*The Collision of Comet Shoemaker-Levy 9 and Jupiter*), which was derived (primarily) from the review papers presented at the international SL9 meeting in Baltimore, Maryland, USA during the spring of 1995. Indeed, much of what is presented in our review here is little more than a cursory summary of a *subset* of the material contained in that volume. In general, the primary research papers, which form the basis of any review, will not be referenced here but can be found in the Cambridge book. We note also that the contributed papers from the Baltimore meeting (which was IAU Colloquium 156) were recently published in a special volume of the journal *Icarus* (vol. 121). Another international SL9 meeting was held in Paris, France in July 1996, and the proceedings from that conference should be available soon.

2. SL9 the comet

Extensive astrometric observations of SL9 were conducted following its discovery. Improving the accuracy of the comet's orbital elements was necessary for refining the timing and geometry of the impacts, which, in turn, determined the observing strategies. For observations with *Galileo*, accurate knowledge of the impact times was especially important as the loss of its high-gain antenna meant that data-taking would be limited and targeted for specific events. Integration of the comet's orbit backwards in time indicates that the comet was probably captured into a jovicentric orbit around 1929 and that the comet passed within 1.3 jovian radii of the planet on 7 July 1992 (Chodas & Yeomans, 1996).

The close passage to Jupiter split SL9 into many fragments, creating the "string of pearls" illustrated in Figure 1. Most of the 20-odd fragments observed during 1993–1994 appeared to lie along a straight line, also called the "train", but nearly half were significantly displaced from the train and were probably produced during secondary fragmentation events (Sekanina, 1996). The off-train fragments generally produced weaker jovian impact phenomena compared to those of their on-train counterparts, providing evidence for diversity in strength, structure, and/or size among the SL9 fragments (Nicholson, 1996).

Figure 1. During a close encounter with Jupiter in July 1992, comet SL9 was tidally disrupted into ~10 fragments, some of which suffered further fragmentation to produce the 21 fragments shown here. This figure is a mosaic of six separate images taken with the HST WFPC2 on 17 May 1994. Each fragment is labeled with its letter designation. The apparent separation of A and W was ~360″, corresponding to a projected distance at the comet of 1.15 × 10^6 km (from Weaver et al. 1995).

Several models were developed to explain the observed morphology of SL9 (cf., Mac Low 1996; Sekanina 1996). The most detailed treatment of the physics of the tidal breakup was given by Asphaug & Benz (1996), who concluded that SL9 was a *strengthless* body having a density of ~0.6 g cm^{-3} and an effective diameter of only ~1.5 km. According to these authors, both the density and size were constrained to lie within ~20% of the nominal values; the number of fragments was a sensitive function of the density while the train length set the diameter of the parent body. Despite the strong arguments presented by Asphaug & Benz, many researchers have found it difficult to accept their conclusion that the comet was truly strengthless. Everyone agrees that cometary nuclei are only weakly-bound objects (they sometimes fall apart even in the absence of significant tidal forces), but it seems difficult to imagine that an icy body would not develop some material strength during its 4.6 billion year lifetime. We also note that one analysis of HST WFPC2 images indicates that the larger fragments were 3–4 km in diameter (Sekanina, 1995), although this result is also controversial.

Trying to categorize SL9 as *either* a comet or an asteroid is probably not very instructive as asteroids that formed in the vicinity of Jupiter probably retained a significant amount of bulk H_2O ice in their interiors, thereby meeting the primary physical criterion for classification as a comet. However, the question of whether SL9 displayed any cometary activity (i.e., outgassing) is an interesting one because it bears on the issue of what produced the observed coma. Here again the results are ambiguous. Sekanina (1996) finds that the production rate of micron-sized dust by SL9 must have been miniscule, while Hahn et al. (1996) argue that SL9 was continously producing a significant number of grains $\geq 5\ \mu m$ in size, but not the usual smaller dust particles.

The composition of SL9 is not strongly constrained by the observations (Crovisier, 1996). No molecular emissions were observed in SL9 spectra, but this is not particularly illuminating as detecting the typical cometary features is very difficult at a heliocentric distance of 5 AU. Mg^+ emission was detected during a single brief observation in July 1995, but this is thought to be associated with the comet's passage through the jovian magnetopause rather than due to traditional cometary activity (Feldman et al., 1996). Curiously, most of our knowledge regarding the composition of SL9 derives from observations of various metals and ions in the plumes associated with the impacts. In these cases, the detected species (Fe, Fe^+, K, Li, Ca, Na, Mn, Mg, Mg^+, Cr, Si, and Si^+) in the jovian atmosphere were certainly of cometary origin, but reliable abundances have not been derived due to uncertainties in the excitation mechanism(s) for the emissions (Crovisier, 1996).

3. Explosions, plumes, splashbacks, bounces, and waves

Valuable insights into what occurred during the collisions of the SL9 fragments with Jupiter can be gleaned by making a detailed examination of the infrared (IR) lightcurves observed during the impacts (Nicholson, 1996). Figure 2 shows one such lightcurve, from the R-impact, and is typical of those observed for most other large impacts.

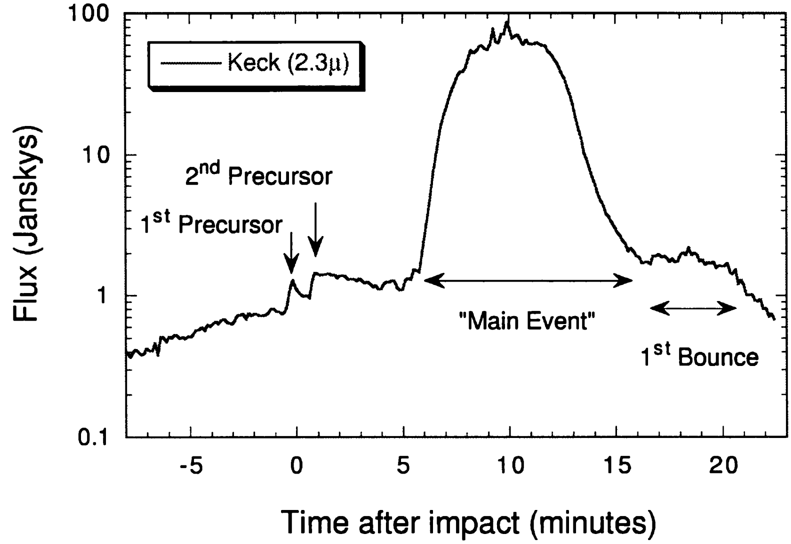

Figure 2. The light curve of fragment R at 2.3μm shows several features that were typical of all the large impacts: two “precursor” flashes followed by a huge “main event” and smaller “bounces”. See the text for further discussion (from Zahnle 1996 using data from Graham et al. 1995).

Initially, observers were very confused by the various features in the lightcurves: the appearance of two peaks called “PC1” and “PC2” (for the first and second precursor peaks, respectively) prior to the onset of a much brighter and more extended peak called the “main event”, which itself was followed by one or more “bounces”. However, eventually a coherent picture emerged that provided a physical explanation for each feature. Figure 3 illustrates the salient points. As the fragment, or bolide, penetrated Jupiter’s upper atmosphere, the corresponding meteor flash was visible to Earth-based observers, but not to the less sensitive *Galileo* instruments. About 10–20 sec after PC1, the *Galileo* instruments recorded a strong flash that was apparently associated with the explosion of the bolide deeper in the jovian atmosphere. This explosion was hidden from view for Earth-based instruments. PC2 corresponds to the emergence of the rapidly cooling fireball above the limb of Jupiter. The plumes became visible after dust formed and rose into sunlight. The dust and gas scattered by the explosion then fell back into the atmosphere, heating it up and producing the huge infrared signals associated with the main event. Some of the impact debris apparently "bounced" off the top of the atmosphere and then re-heated the atmosphere upon its return.

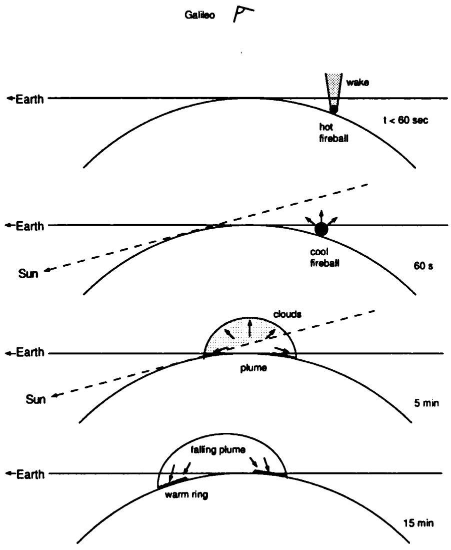

Figure 3. Viewing geometry for a typical SL9 impact. The first precursor IR signal corresponds to the fragment entering the atmosphere. The second precursor corresponds to the fireball rising into direct view from Earth. The plume was observed in scattered sunlight, and the bright IR "main event" was detected after the plume splashed back into the jovian atmosphere (from Zahnle 1996).

A massive effort was mounted by several groups to model the collisions of the SL9 fragments with the jovian atmosphere (cf., Crawford 1996; Mac Low 1996). Generally, the problem was divided into two parts, the entry phase and the fireball/plume phase. The bolide explosion naturally provides the endpoint of the entry phase, and the output from that model is fed as input to the models of the fireball/plume phase.

A simple analytic model, sometimes called the "pancake" model because a severe flattening of the bolide is produced by the pressure differential between the along-trajectory and transverse directions, gives results that are surprisingly close to those produced by much more sophisticated numerical models. Contrary to intuition, the models show that the explosion depth is essentially independent of the bolide's material strength. Apparently the bolide's cross-sectional area (S) is the property that most strongly affects

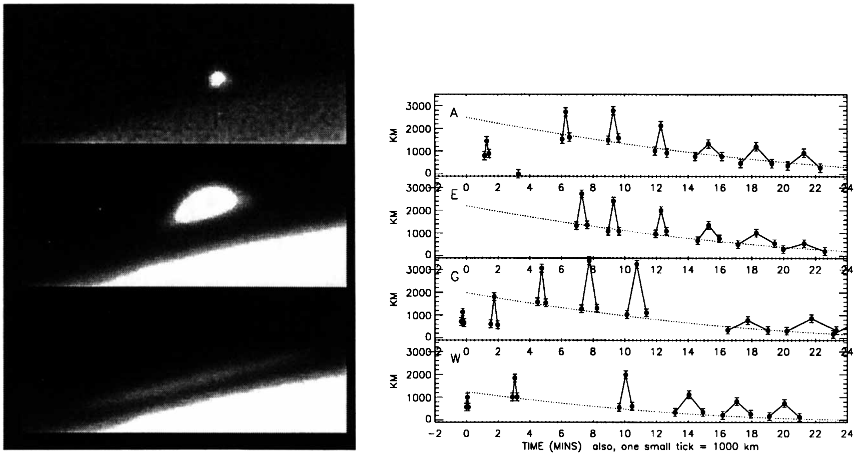

Figure 4. The left panel shows the evolution of the plume following the impact of the G fragment of comet SL9 on 1994 July 18. The three images (top to bottom) were taken 2, 11, and 18 mins after impact. The right panel shows the plume altitude and width as a function of time for four different impacts. The x-axis gives both the time from impact (large ticks) and plume width (small ticks), while the y-axis gives the height above the 100 mbar level in Jupiter's atmosphere. The dashed lines give the calculated height of the jovian shadow above the 100 mbar level. All observed plumes reached approximately the same maximum altitude. Adapted from Hammel (1996).

the results. The energy deposition per unit length is directly proportional to the cross-sectional area, while the depth of maximum energy release (i.e., the explosion point) scales as $S^{0.75}$. So, in principle, observations of the fireball's energy could be combined with modeling to estimate the bolide's cross-sectional area. However, in practice definitive results cannot be obtained this way because the efficiency with which the energy dissipated by the passage of the bolide through the atmosphere is converted into luminous energy is not accurately known.

It was originally hoped that modeling of the spectacular plumes rising over the jovian limb might constrain the impactor sizes. However, as Figure 4 illustrates, the maximum height reached by the plumes was essentially the same for fragments having very different pre-impact brightnesses. This seemingly counter-intuitive result is easily explained by the pancake model and is confirmed by the detailed calculations (cf., Crawford 1996; Mac Low, 1996). While the energy deposition per unit length along the trajectory is proportional to the bolide's cross sectional area, the specific energy of the heated column (i.e., the energy divided by the mass) is independent of the impactor's size. Since the characteristic velocity of the heated gas, which determines the plume height, is equal to the square root of twice the specific energy, all plumes should go approximately to the same altitude.

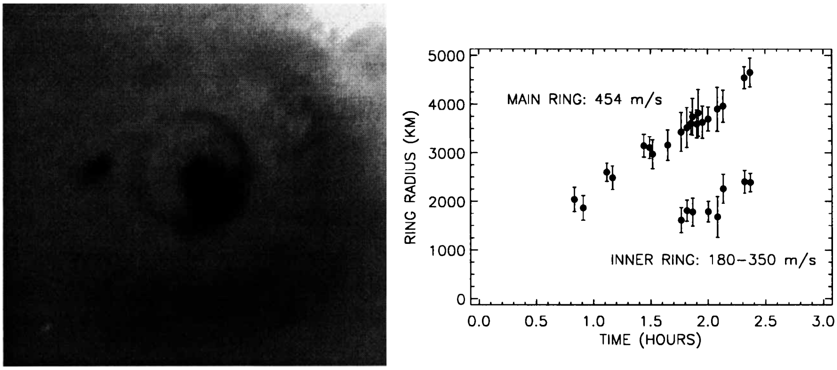

Figure 5. The left panel shows the G site 1.66 hrs after impact, re-projected to simulate the view as seen from directly above the site. The morphology is similar to that observed for all of the major impacts: large crescent-shaped ejecta offset to the southeast from the dark streak near the point of impact, with fainter traces of dark material extending completely around the site. The prominent narrow ring expands with time, as if it were associated with the passage of a wave. A fainter ring, which also expands, is located inside the main ring. The right panel shows the radius of the two rings as a function of elapsed time after impact, after combining data from all the impacts that showed rings. The main ring measurements lie along a single line, indicating that the speed is independent of explosion energy. Adapted from Hammel, 1996.

HST images of five different impact sites (A, E, G, Q1, and R) showed a relatively narrow ring of debris that propagated outward with time. Fainter inner rings, which also seemed to move outward, were observed at the G and E sites. Figure 5 shows an image of the G-impact site and a plot demonstrating that the rings had a *constant* speed of either 450 or 210 m s^{-1} (for the brighter and fainter rings, respectively). These data strongly suggest that the rings are due to the propagation of waves. Ingersoll & Kanamori (IK96; 1996) considered many types of waves and concluded that the rings were probably associated with *tropospheric gravity waves* (TGW) in the jovian water cloud. The H_2O abundance in the atmosphere is essentially the only physical quantity that affects the speed of the TGW waves, and IK96 found that the O/H ratio must be $\sim$10 times solar in order to match the observed speed for the faster wave. Unfortunately, the results from the *Galileo* entry probe (Niemann et al., 1996) indicate that the O/H ratio is *sub-solar* in the jovian atmosphere, apparently in contradiction with the principal hypothesis proposed by IK96. Thus, there is currently no explanation that satisfactorily accounts for the observed propagation of the rings.

4. Molecules in the aftermath

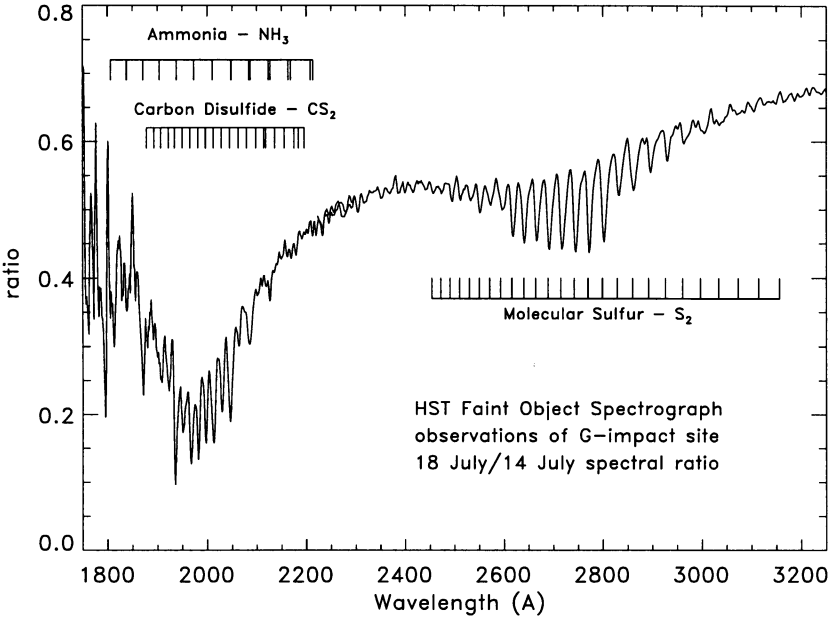

Figure 6. *HST* spectra of the G impact site taken ~3-4 hrs after the impact on 18 July 1994 divided by similar spectra taken on 14 July 1994 well before the impact. The principal absorption features are due to S_2, CS_2, and NH_3. The data shortward of ~1850 Å are unreliable due to contamination from grating scattered light. Adapted from Noll et al. (1996).

Many new molecules were detected in Jupiter's atmosphere following the impacts. Figure 6 is an HST spectrum of the G-impact site that clearly shows absorption bands due to S_2, NH_3, and CS_2. Modeling of these spectra indicates that H_2S may also have been detected (Yelle & McGrath, 1996), although the observed absorption could also have been produced by aerosols (Atreya et al., 1995). Observations at IR, mm, and sub-mm wavelengths revealed several other species including CO, H_2O, CS (which was also detected in HST spectra of the S-plume), HCN, C_2H_4, and possibly PH_3 (Lellouch, 1996). Most of these molecules (CO, H_2O, S_2, HCN, CS, OCS, CS_2, and C_2H_4) apparently were confined to very high altitudes (i.e., pressures less than ~1 mbar) and were probably associated with the fall-back of plume material into the upper atmosphere. Unlike the other species, NH_3 was confined primarily to pressures greater than ~5 mbar (Yelle & McGrath, 1996). Analysis of the HST data suggests that the impacts heated the ambient jovian NH_3 clouds (near the 600 mbar level) causing the upwelling of large amounts of warm NH_3 gas into the stratosphere (the jovian tropopause is at a pressure level of ~100 mbar).

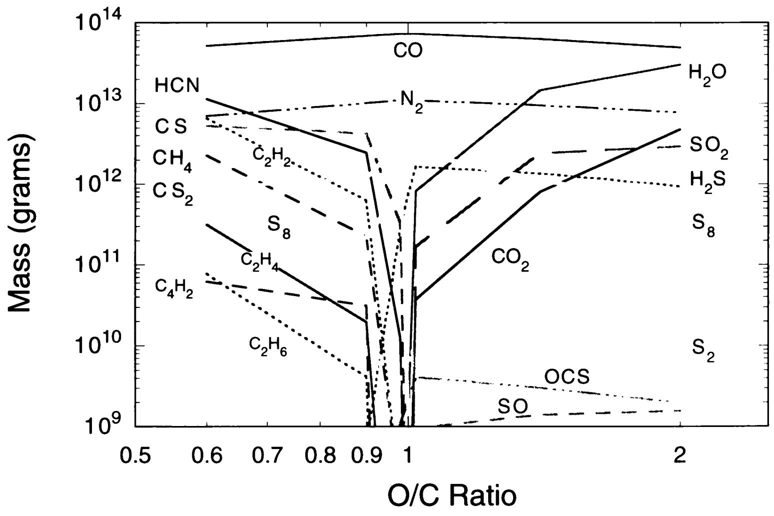

Figure 7. This figure shows the total production of various molecules plotted as a function of the comet's O/C ratio as a result of the shock chemistry in a plume consisting of 50% jovian air and 50% cometary matter for a 10^{14}g comet. Production of CO dominates in all cases, which is consistent with the observations. However, significant amounts of both reduced and oxidized species are observed, indicating that the actual chemistry was more complex than was assumed in the model.

Abundances have been derived for most of the species associated with the impacts. The estimated total mass for each molecule at a "large" impact site is given in Table 1 (adapted from Lellouch 1996). No values are listed for PH_3 and H_2S because of the large uncertainties for these cases. As is evident from the table, CO is by far the dominant species, and this is consistent with shock chemistry models of the plume (Zahnle, 1996). However, unlike the chemical models, which predict that either mostly oxidized species (when $O/C > 1$) or mostly reduced species (when $O/C < 1$) will be created, the SL9 impact sites produced significant amounts of both oxidized and reduced species.

Assuming that all of the O in the CO came from the impactor, and that the impactor had an O abundance similar to that of comet Halley, the observed mass in CO would require an impactor mass of $\sim 3 \times 10^{14}$ g, which corresponds to a fragment diameter of ~1 km if the density is 0.6 g cm^{-3}. Thus, the mass of a *single* large impactor is already ~30% of the mass of the SL9 progenitor body, using the Asphaug & Benz (1996) prediction for the latter quantity. The large CO mass is one of the few strong arguments against the "small fragment" paradigm for SL9 (the other main one being Sekanina's [1995] analysis of HST images of the SL9 fragments, which gives effective diameters of ~4 km for the larger fragments). Otherwise, most of the observational data are consistent with fragment diameters of ≤ 0.7 km, as predicted by the tidal disruption models (see Figure 7).

TABLE 1. Masses of detected molecules for a typical large impact

Molecule	Mass (g)
CO	2.5×10^{14}
NH_3	1×10^{13}
C_2H_4	3×10^{12}
OCS	3×10^{12}
H_2O	$\geq 2 \times 10^{12}$
S_2	$\sim 7 \times 10^{11}$
HCN	6×10^{11}
CS	5×10^{11}
CS_2	1.5×10^{11}
PH_3	??
H_2S	??

The molecules produced in the jovian atmosphere by the impacts were expected to evolve with time due to UV photolysis, chemical reactions, vertical and horizontal transport, and condensation/aerosol formation. One-dimensional photochemical models provided reasonably accurate predictions for the temporal variation of NH_3 and HCN, but did not do as well for S_2 and CO, both of which were not as stable as predicted by the models (Moses, 1996). Most traces of the SL9 impacts had vanished from Jupiter's atmosphere after about one year.

5. Conclusions

Some aspects of the SL9-Jupiter impacts are reasonably well understood. A consensus has developed regarding the interpretation of the lightcurves observed during the impacts, in which physical cause and effect are identified. Impact models seem to provide a reasonably good description of the energy dissipation during the bolide's passage through the atmosphere, the production of a hot fireball, the development of a plume that extends to altitudes of ~3000 km, the condensation of dust within the plumes, the heating of the atmosphere following the plume splashback, and the general morphological characteristics of the impact scars.

However, many important issues regarding the SL9-Jupiter impacts remain unresolved and/or controversial. There is no general agreement on the size, density, or strength of the SL9 progenitor body, no clear agreement on the depth of bolide penetration in the jovian atmosphere, and no good explanation for the production of debris rings that seemingly propagated outward from the impact sites. While abundance determinations for some species are solid, many remain highly uncertain. Shock chemistry is capable of creating virtually all of the molecules observed at the impact sites, but the presence of significant abundances of both oxidized and reduced species defies any simple explanation. Photochemical models correctly predict the temporal evolution of some species, but not of others.

Although we still do not know all the answers, the collision of SL9 with Jupiter was clearly a significant scientific event. There is now little doubt that catastrophic collisions play a major role in the evolution of our solar system, and studies of the SL9-Jupiter impacts provided a major step forward in our quest to understand them.

Acknowledgements

In preparing this review, I relied heavily on the excellent review chapters contained in the book *The Collision of Comet Shoemaker-Levy 9 and Jupiter*, which was published by Cambridge University Press in 1996. To the authors of those review chapters, I express my sincere thanks for doing such a nice job. Of course, any errors that have crept into my review are solely my responsibility. I also apologize to the CUP authors whose work I have completely neglected in this review; there is only so much that I can include within my page allocation. I especially thank Erik Asphaug, Heidi Hammel, Wing Ip, Mordecai-Mark Mac Low, Melissa McGrath, Julie Moses, Keith Noll, Phil Nicholson, Bob West, and Kevin Zahnle for providing figures, which I used either in my oral presentation or in this chapter. Thanks also to Erik Asphaug and Zdenek Sekanina for countless discussions regarding the tidal disruption of SL9. With pleasure I thank the organizers of IAU Symposium 178 for inviting me to review the SL9-Jupiter impacts, and for providing partial financial support for my attendance at the wonderful meeting in Leiden. Finally, I acknowledge financial support from NASA through grant number GO-5624 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

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Discussion

Van Dishoeck: Could you comment on the abundance and excitation of H_3^+?

Weaver: H_3^+ emission was observed at the impact sites at 45°S latitude and at (or near) the magnetic conjugate points in the northern hemisphere. These emissions demonstrate that the impact generated a population of ionizing particles at the impact site, which were then transported to the North along magnetic field lines. The emissions were time-variable and the ratios of North to South intensities were much larger than typical values. The observed behavior seems roughly in agreement with pre-impact predictions from Cravens (Geophysics Research Letters 1994, 21, 1071) who showed that the injection of H_2O + CO into the impact site would short-circuit the plasma current that powers the southern aurora while increasing the current to the North. Regarding the H_3^+ abundance, I do not know the specific numbers but I would expect that they are close to the values derived under normal auroral conditions since the intensities are comparable.

Saxena: What is the abundance ratio of C_2H_4 relative to H_2O in Comet SL9? Is it of the same order, i.e., 1–2 %, as in comet Halley?
Weaver: While C_2H_4 was detected at the impact sites, we do not know whether or not C_2H_4 was present in SL9 itself. I should also point out that there has been no accurate determination of the C_2H_4 abundance in p/Halley.

Li: The detected abundance of CO is $\sim$ 100 times higher than that of H_2O. It is difficult to understand that such a high CO abundance comes from the comet nucleus. Is it possible that the CO is also contributed by the evaporation of the fluffy cometary dust particles distributed along the nucleus, as is the case with comet Halley?
Weaver: The molecules observed in the impact sites were presumably produced by shock chemistry during the splashback of material into Jupiter's atmosphere. The molecular content of the comet was probably completely destroyed during the impact, which means that the molecular composition of the impact sites might be unrelated to the molecular composition of the comet. Instead, the molecular composition of the impact site was determined by the elemental composition of the comet and the (pressure, temperature) temporal history experienced by the mixture of cometary and jovian matter in the plumes.

Pecker: The pre-collision orbit seems to be close to Jupiter for many years, coming from the outside only years ago. On the other hand, you find little water in the spectra of the after-collision. What about the posibility that the "comet" SL9 was indeed either a *satellite* of Jupiter, deviated by some local interaction, or even an *asteroid* from the asteroid belt, captured by Jupiter (which must be a common phenomenon)?
Weaver: Yes, there was a lot of discussion about whether SL9 was a comet or an asteroid. The presence of a circularly symmetric coma that persisted throughout most of the period that the comet was observed favors the view that SL9 was indeed a comet. More generally speaking, there are no observations that contradict the hypothesis that SL9 was a typical Jupiter-family comet.

Zeng: Why did people fail to observe the rotational line of CO $J = 1 \rightarrow 0$?
Weaver: The CO $J = 1 \rightarrow 0$ line was observed but I only showed the $J = 2 \rightarrow 1$ observations.

Scappini: Is the enhancement of NH_3 in the SL9 / Jupiter impact due to modified excitation conditions or because the bolides hit the Jupiter solid ammonia layers?
Weaver: The NH_3 abundance in the jovian stratosphere was dramatically increased following the impacts, but this stratospheric NH_3 was much deeper in the atmosphere than most of the other impact species (e.g., CS_2. S_2, etc.). Therefore it is thought that the NH_3 in the stratosphere was due to upwelling of NH_3 from the troposphere that had been heated by the impacts.