Comet Shoemaker-Levy 9 Collides with Jupiter

THE CONTINUATION OF A UNIQUE EXPERIENCE

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After the Storm

The recent demise of comet Shoemaker-Levy 9, for simplicity often referred to as "SL-9", was indeed spectacular. The dramatic collision of its many fragments with the giant planet Jupiter during six hectic days in July 1994 will pass into the annals of astronomy as one of the most incredible events ever predicted and witnessed by members of this profession. And never before has a remote astronomical event been so actively covered by the media on behalf of such a large and interested public.

Now that the impacts are over and the long and tedious work to reduce the many data has begun, time has come to look back and try to appreciate what really happened. This may be easier said than done, for few of the many actors were able to experience the full spectrum of associated events. Most of the astronomers who were directly involved in the observations hardly had time to do anything else, and the interested laymen who watched on their TV screens the frantic activity all over the world were not in the best position to get a balanced overview from all of this. At this moment, two months later, more has become known about the many observational programmes, and the first indications of the exciting science that will ultimately result from the enormous data sets have begun to emerge.

The 22nd General Assembly of the International Astronomical Union, held during the second half of August in The Hague (The Netherlands), offered the first opportunity to learn in more detail about the outcome from the very successful, world-wide observational efforts. Two four-hour sessions were ably organized at very short notice by Catherine de Bergh, David Morrison, Mike A'Hearn and Alan Harris. More recently, a meeting of the La Silla observers took place on September 12 at the ESO Headquarters in Garching.

Here follows a short and most certainly quite incomplete overview of the current status of the SL-9 observations and their great potential for new knowledge, based on the presentations during these meetings.

Six Hectic Days in July

ESO was but one of many professional observatories where observations had been planned long before the critical period of the "SL-9" event, July 16–22, 1994. It is now clear that practically all major observatories in the world were involved in some way, via their telescopes, their scientists or both. The only exceptions may have been a few observing sites at the northernmost latitudes where the bright summer nights and the very short evening visibility of Jupiter just over the western horizon made such observations next to impossible. In addition, it is most gratifying that legions of amateur astronomers immediately went into action when it became known that the changes on Jupiter could be perceived even with very small telescopes.

During the week of the impacts, press conferences were held at many observatories; ESO arranged a series of very well attended media events in Garching and in Santiago de Chile. A day-to-day chronicle of what happened during this period may be found in the "ESO SL-9 News Bulletin" of which a total of 14 issues were prepared between July 10 and 26. The full text, as well as many images and graphics may still be obtained from the ESO WWW Portal (http://http.hq.eso.org/eso-homepage.html) or via anonymous ftp (ecf.hq.eso.org; directory: pub/sl9-eso-images).

The observing possibilities were best from the southern hemisphere and, by good fortune, the weather in South Africa and Australia was very co-operative during the critical week. It was less so in Chile, where La Silla, Cerro Tololo and Las Campanas were effectively clouded out during the latter part of the impact period. Long series of excellent observations were also made from La Palma and Calar Alto (Spain), as well as from Hawaii and observatories in Japan. Although details are still lacking, it is apparent that the programmes at many observatories in other countries were also very successful. However, a complete list of all SL-9 observations has yet to be compiled.

At ESO, ten telescopes were in operation during the first nights and, as in other places, an extremely rich data material was secured. It quickly became evident that infrared observations, especially imaging with the far-IR instrument TIMMI at the 3.6-metre telescope, were perfectly feasible also during daytime, and in the end more than 120,000 images were obtained with this facility. The programmes at most of the other La Silla telescopes were also successful, and many more Gigabytes of data were recorded with them. Brief reports from some of these programmes are brought in this *Messenger* issue. The fact that a significant amount of observing time was allocated after the main event was over, turned out to be a major blessing, and some of the most interesting data were obtained during the period immediately following the last impact on July 22.

It is not yet possible to estimate the total amount of SL-9 observational data now available at observatories all over the world, but it may well run into many tens, perhaps hundreds of Gigabytes. One of the most urgent problems is now to get an overview of all these data so that observers from different sites will be able to establish effective collaborations. It has also become evident that in order to understand the very complex processes around the impacts, in particular the detailed evolution of the plumes ("fireballs") that rose above the impact sites, it will be necessary to intercompare data from many different instruments with a variety of techniques, ranging from the high-resolution, extremely detailed UV and visual images of the Hubble Space Telescope, to "movie-like" image sequences obtained with infrared instruments like TIMMI, and long-exposure, high-dispersion spectra of these plumes obtained with more classical spectroscopic equipment.

Much Hard Work Ahead

The observed effects were extremely spectacular, from the incredibly bright "fireballs" (or "plumes") which rose above the limb of the planet, to the intricate and changing forms of the resulting "pancake" clouds, of which several – to the greatest surprise of many astronomers –

are still visible at the end of September, although less prominent than before.

Until now, most observational programmes have not progressed much beyond a purely phenomenological description of what was seen. However, it is also the task of all astronomical research to progress far beyond such a simple description; the ultimate goal is of course to understand the physical processes behind the event. This calls for "reduction" and "interpretation" of the data. The first is a long and complicated procedure, involving different types of calibrations in order to "clean" the raw data from all possible, extraneous effects and to extract the quantitative information that is needed to arrive finally at a global understanding of what really happened.

For this reason, most observers have so far only been able to answer a few of the many questions which are now being eagerly asked from all sides. Having been treated to real fireworks of "real-time science" and "quick-shot guesstimates" (greatly facilitated by the incredibly successful initiation during this event of the "astronomy information superhighway", especially via *internet*), and having been confronted (not to say "spoiled"!) with hundreds of impressive pictures of mushroom clouds in the southern hemisphere of Jupiter, the media and the public now keep asking when we will finally know what all of this means.

In this connection, it is sometimes difficult to explain that while modern astronomical observing techniques have become extremely efficient – and this is the main reason that it was possible to respond to the unique challenge of the SL-9 event in such an impressive way and to obtain such a rich data material – this does not mean that this science has also progressed to the point where the data reduction and the astrophysical interpretation can follow at the same pace. On the contrary, I think that a major lesson of this event is that more resources than before must now be directed towards this area – otherwise we are at high risk to drown in the future data floods from the new giant telescopes like the VLT and its hosts of incredibly effective instruments.

Impact Times for Fragments of Comet Shoemaker-Levy 9

The following list of impact times (UTC times received at Earth, i.e. light-time corrected) was prepared by Don Yeomans and Paul Chodas (JPL) in early August 1994.

Fragment	*Date*	*Prediction (h:m:s)*	*Accepted impact time and 1 σ error*
A	*July 16*	*20:00:40*	*20:11:00 (3 min)*
B	*July 17*	*02:54:13*	*02:50:00 (6 min)*
C	*July 17*	*07:02:14*	*07:12:00 (4 min)*
D	*July 17*	*11:47:00*	*11:54:00 (3 min)*
E	*July 17*	*15:05:31*	*15:11:00 (3 min)*
F	*July 18*	*00:29:21*	*00:33:00 (5 min)*
G	*July 18*	*07:28:32*	*07:32:00 (2 min)*
H	*July 18*	*19:25:53*	*19:31:59 (1 min)*
J	*July 19*	*02:40*	*Missing since 12/93*
K	*July 19*	*10:18:32*	*10:21:00 (4 min)*
L	*July 19*	*22:08:53*	*22:16:48 (1 min)*
M	*July 20*	*05:45*	*Missing since 7/93*
N	*July 20*	*10:20:02*	*10:31:00 (4 min)*
P2	*July 20*	*15:16:20*	*15:23:00 (7 min)*
P1	*July 20*	*16:30*	*Missing since 3/94*
Q2	*July 20*	*19:47:11*	*19:44:00 (6 min)*
Q1	*July 20*	*20:04:09*	*20:12:00 (4 min)*
R	*July 21*	*05:28:50*	*05:33:00 (3 min)*
S	*July 21*	*15:12:49*	*15:15:00 (5 min)*
T	*July 21*	*18:03:45*	*18:10:00 (7 min)*
U	*July 21*	*21:48:30*	*21:55:00 (7 min)*
V	*July 22*	*04:16:53*	*04:22:00 (5 min)*
W	*July 22*	*07:59:45*	*08:05:30 (3 min)*

In setting forth the accepted impact times given in the final column, the priority of the various available techniques is as follows:

1. *GLL PPR timing (fragments H and L).*
2. *When definitive flash times are available, with subsequent plume observations noted about 6 minutes later), we generally took the impact time as one minute before the flash time since the PPR instrument recorded its first signals about one minute before the reported flash times (fragments D, G, Q1, Q2, R, S, V, and W).*
3. *Estimates determined from HST longitudes.*
4. *Estimates determined from first plume observation minus 6.2 minutes.*
5. *Chodas/Yeomans prediction with empirical adjustment of + 7 minutes.*

The impact times for fragments A, C, E, K, and N were determined by considering the ephemeris prediction error (about 7 minutes early for most fragments), the times determined from the HST longitude estimates (uncertainty = 3–4 minutes or more) and the times determined from plume observation times (impact time = plume observation time less 5–8 minutes). An effort was made to consider and balance these three factors and the uncertainties on the estimated impact times reflect our confidence level. For fragment F, the impact time was determined using the ephemeris prediction and the Lowell Observatory estimate of when the F spot was seen on the terminator. In the absence of any quantitative impact time observations for fragments P2, T, and U, only the ephemeris prediction was used (plus 7 minutes). The impact time estimate for fragment B is based upon observatory reports and is relatively uncertain because the impact time occurs before the ephemeris prediction and well before the estimate determined from the HST longitude estimate.

The Comet Fragments

So what have we learned so far about the comet, about Jupiter and about the impact process itself? As expected, unique observations like these have led to important new knowledge, but at the same time they do not fail to raise a host of new and difficult questions.

First of all, the comet was obviously a complex body. From the diversity of the impacts and their observed effects, it seems that there were important differences between the individual fragments; this provides an indication that the cometary parent body must have been an inhomogeneous object. On the other hand, polarimetric measurements of the dust clouds around the individual nuclei do not show any perceptible differences, so the dust produced by them appears to have been rather similar. Some nuclei, which were thought to be "large" because they were surrounded by much dust and were relatively bright, turned out to produce comparatively small effects during impact, and in other cases, it was just the opposite. The famous example is the first fragment (A) that took everybody by surprise with its unexpectedly violent impact effects, while the second (B), although twice as bright, showed no observable effects at the moment of impact, although the corresponding atmospheric "hole" was later seen.

No gas was ever observed in the comet, despite extreme efforts to detect at least the usually strong cometary CN lines with the ESO NTT. So the fragments apparently produced only dust comae and tails. Is this reasonable? Would not the break-up process have been accompanied by the escape of at least some gas, and would not the later release of dust have shown a small amount of gas at some time? Could it be that the comet, after all, was of an unusual type, or was the dust production in this case not driven by gas, as is commonly thought? Or does this imply that we are mistaken in our present assumptions about how a "normal" comet ought to behave under the present circumstances? It was most probably not an asteroid though, as has also been surmised, the disappearance from view of some of the fragments makes this very unlikely. Another strange and unexplained effect is the elongation of the images of the fragments in the direction of Jupiter that was clearly observed during the last few days before the impacts. We obviously do not yet fully understand the dynamics of the dust in Jupiter's vicinity.

The Impact Process

It appears that the "meteoric" phase of the impacts, that is the entry of the fragments into the Jovian atmosphere and the expected heating of their surfaces by the associated friction, was not observed from the ground in reflection from the Jovian moons as predicted. The Galileo images of the W event which have now been transferred do show a light flash that lasted a few seconds, but it was not particularly strong and would probably not have been detected in reflection from a Jovian moon by the available ground-based instruments. Why didn't the cometary fragments glow stronger during their encounter with the upper atmosphere? The reports of a possible colour change of the moon Io during the time of some of the impacts are still unexplained. And there are no obvious detections of IR reflections from Jupiter's dust ring.

It does appear that the total energies liberated were larger than anticipated, but it will not be possible to make accurate estimates, before the processes in and around the resulting plumes are better understood. From the amount of measured infrared emission alone, it seems that the cometary fragments must have been at least several hundred metres across in order to provide enough kinetical energy, but this is most certainly a lower limit only. Other estimates point towards the release of perhaps 1 million Megatons of energy or even more during the larger impacts – this would then correspond to diameters well over one kilometre for the largest fragments.

It appears that it may already now be possible to determine the approximate depth of the penetration by the fragments into the atmosphere. The observations of large amounts of NH_3 and relatively little H_2O in some of the plumes (see below) indicate that the most energetic explosions most likely took place between the second (assumed to contain NH_4SH aerosol) and the third (H_2O) cloud layers.

The Fireballs and the Plumes

The detailed circumstances of the final explosions and the resulting fireballs pose one of the greatest interpretative problems of the SL-9 event. Several ground-based infrared instruments detected "precursors" in the form of small and bright, rapidly expanding clouds appearing above the limb within about one minute after the presumed impact times as determined by the all-disk photometer onboard Galileo. The Hubble Space Telescope high-spatial-resolution near-IR and visual images show the same phenomenon.

It is not at all obvious what this signifies, but it is now generally believed that this is the image of a rising fireball (during its continued development also referred to as "mushroom cloud" and "plume"), still in Jupiter's shadow and shining in the optical region by its own light because of its very high temperature (values in excess of 10,000 degrees have been mentioned). Rising ever higher while it rapidly cools, the total intensity of the plume above the impact site first decreases, but as it continues to grow and the upper parts move into sunlight, the optical brightness again increases as more and more sunlight is reflected.

The cooling process leads to a sharp maximum of radiation in the infrared spectral region, some 10–15 minutes after the impact – the moment of maximum and the overall shape of the light curve is determined by a complex combination of temperature, size of the plume and visibility (geometry), into which enters the effect of the rapid Jovian rotation that quickly brings more and more of the plume into view from the Earth. It will be very difficult to untangle these effects from each other and to arrive at a consistent description of the plume development. Moreover, some pronounced humps in several of the IR light curves point towards multiple impacts, e.g., at the L- and R events, adding yet another formal difficulty to this procedure.

The Long-Term Atmospheric Features

The further development of the plumes is also not entirely unambiguous, although there is now a general consensus that the debris from the explosion in the end settles into "pancake"-shaped clouds at an altitude high above the visible clouds that corresponds to about the 1 millibar level in the atmosphere. Several types of observations indicate that these clouds are made up of "haze" (aerosols) and not by molecules (e.g., their IUE UV spectra are rather flat). In the IR spectral region, they look bright because of reflected sunlight and they hide the features below. In the visible spectral region, they are transparent at many wavelengths. They are generally darker than the Jovian cloud layer, except when viewed at the wavelengths that correspond to the strongly absorbing methane bands; here the clouds again appear bright on the very dark background.

The excellent HST images, for instance those obtained of the G impact site just after its appearance at the limb, show a very complex structure near the impact sites. In the middle is a "black" hole, which probably represents the material around the "funnel" excavated by the impacting fragment. To begin with, it is surrounded by several, partly incomplete "rings" of rather short lifetime. The inner ones are possibly shock waves in the atmosphere moving outward from the impact site, while the outer, broad horseshoe-shaped features appear to represent the resettling debris that was lifted to very high altitudes before coming back down. When compared to impact experiments in the laboratory, this pattern fits quite well with the direction and the 45° angle of entry of the cometary fragments.

It is in this connection also interesting to note that the very bright sky observed in Europe and Asia during the night following the Tunguska impact on July 30, 1908, may now be explained by a similar effect, namely the very rapid deposition over a large area of debris (dust) that moves along high, ballistic orbits from the impact site. Moreover, the trail of the Tunguska object was described as a large smoke column. This would seem to strengthen the interpretation of this terrestrial event as being of a basically similar nature.

Many of the later impacts hit the sites of earlier ones and the resulting geometric configurations soon became very complex. The further development of the cloud patterns has since been followed at many observatories. While the smaller clouds have (almost) disappeared in the meantime, the larger complexes are still visible, also in smaller telescopes. Diffusion in longitude because of the wind in the Jovian atmosphere set in early, and after some time, spreading in the north-south direction was also observed. Two months after the last impact, the cloud contours continue to be gradually washed out and there is an increased degree of mutual overlap. Nobody knows at this moment how long these features will continue to be visible. It is unfortunate that the monitoring of these changes will soon be interrupted for some time while

Jupiter moves behind the Sun as seen from the Earth.

The Composition

The composition of the plumes was investigated by spectroscopy in many different wavebands. While no entirely new molecules have been found during quick-looks at the very large data material, it is expected that further analysis will eventually make it possible to document in some detail the complex chemical processes that took place during the early phases of expansion and subsequent collapse. The following elements and molecules have been seen in the spectra: Li, Na, Mg, Mn, Fe, Si and S; NH_3, CO, H_2O, HCN; H_2S, CS, CS_2, S_2; CH_4, C_2H_2,C_2H_6, and possibly others.

Of particular interest is here the detection of the strong Li line at 6708 Å in emission: from where does this element come, the comet, Jupiter or both? I am not aware that Lithium has ever been observed in any comet. Enormous quantities of molecular sulphur (S_2) were seen in high-dispersion UV spectra obtained with the HST. A very first estimate indicates no less than $\sim 10^{15}$ g in one fireball, or almost 1% of the estimated total mass of the nucleus of P/Halley ! Although there was surprisingly much sulphur in P/Halley (about 9% of the carbon content), this material must come mostly from Jupiter and this observation provides the first unambiguous proof of the (predicted) presence of large amounts of this element in the deeper layers of the Jovian atmosphere. One of the greatest mysteries may be the almost complete absence of water in the plumes – in 1986, P/Halley was found to consist to 80% of water ice – where did the cometary water go? Or maybe the question should be reformulated: with which elements did these hydrogen and oxygen atoms later recombine to form new molecules?

Very rapid spectral changes were seen in the plumes. For instance, while emission lines of Li, Na, K and Ca were present in the first spectrum of the L impact plume obtained at the Pic-du-Midi observatory, the next spectrum only 20 minutes later was entirely different. At ESO, the IRSPEC spectra obtained at the NTT showed highly excited CH_4 emission in the first spectra of the H impact site. The intensity decreased very rapidly until it could no longer be seen 30 minutes later. KAO far-IR observations also showed hot CH_4, and submillimetre HCN spectra obtained with the JCMT telescope at Hawaii showed line broadening in areas of several impacts.

It appears unlikely that a fully coherent picture of what happened in the plumes will ever be obtained unless an unprecedented synthesis of the complex information in all available spectra is attempted. At this moment, condensation of CO and possibly other species is thought to play an important role. Moreover, the fact that for instance the PH_3 emission did not change much indicates that the deep atmosphere of Jupiter was not altered very much by the impacts.

The Jovian Magnetosphere

Another, very interesting result is the detection of enhanced auroral activity in the Jovian atmosphere which is clearly related to the impacts. This was first seen in the UV images from the HST that showed a strong effect near the northern pole. It is assumed that this is due to the rapid motion along the magnetic field lines of charged particles created at the impact site. The unexpected detection of symmetric emission patterns in the northern hemisphere in IR lines of H_3^+ and H_2, as seen in the days after July 22 by IRSPEC, is another strange phenomenon that may possibly be contributed to the same mechanism.

The predictions about possible effects of cometary dust entering into the Jovian magnetosphere ranged from negligible to dramatic. One uncertain element was of course the amount of dust, but it was very difficult to model the physical processes. The same was true for the overall effects on the faint Jovian dust ring because of dust accumulation and so were the changes in the Io torus because of charged cometary particles.

While there have been no reports about observations of changes in the Io torus or in the Jovian dust ring, the first accounts about apparent variations in the Jovian radio emission may not have taken fully into account its inherently variable nature, due to the changing aspects of Jupiter's offset dipole field. Indeed, there were conflicting claims during the first days, ranging from no changes at all, e.g. the first summary of the observations from the Ulysses spacecraft, to very significant changes purportedly registered in some places.

However, after the firm establishment of valid baseline models it has become clear that a gradual, but significant enhancement of the radiation was actually observed, amounting to about 20 % at 13 cm wavelength. Increases were also seen at longer wavelengths, perhaps even in excess of this figure. An interesting effect was the apparent inward motion of the "radiation points", as observed at Westerbork and with the VLA. The physical reason for this is not yet established.

Seismology

What about the seismological measurements which may finally give us the first opportunity to elucidate the inner structure of Jupiter? It is still too early to say anything, except that the necessary observations, in the form of more than 100,000 infrared images, have indeed been secured and that the extremely tedious data analysis has already started. It will take a long time to eliminate all the instrumental effects and even longer to extract any faint, seismic message from these frames. Incidentally, certain reports about ring-shaped structures which were purportedly seen on some CCD frames and which were provisionally interpreted as possible waves in the Jovian atmosphere, are now believed to be instrumental and/or reduction artefacts.

Future SL-9 Meetings

The analyses of the voluminous SL-9 data continue, but it is unlikely that a coherent picture of what really happened will emerge before next year. In the meantime, the observers stay in contact and have begun to exchange information about this process. They will also meet at regular intervals. The first major presentation will take place during a one-day session at the DPS meeting in Bethesda near Washington DC on October 31, 1994. A major IAU colloquium is planned for May 1995 at the STScI in Baltimore, Maryland, USA.

The possibility of holding a smaller meeting at ESO in February 1995, mainly with the participation of observers in Europe, is now being looked into and a decision is expected to be taken by mid-October 1994. For the latest information, please consult the ESO WWW Portal (address see above).

Conclusions

SL-9 is no more. By its glorious death it has provided us with an unequalled and exciting opportunity to study the inner parts of a comet and to analyse the Jovian atmosphere. It also has enabled us to learn what they do to each other when they collide at 60 km/sec.

When asked what the preliminary information from this event can tell us about a similar one on the Earth, Mike A'Hearn, the summary speaker at the IAU General Assembly sessions on SL-9, said that there is now little doubt that a cometary impact of the same nature and dimensions would not dissipate much energy in the upper atmosphere and that it would obviously reach the Earth's solid surface and produce the associated effects. The continued study of the SL-9 observations will most certainly also cast more light on this very relevant terrestrial problem.