The Comet - Jupiter Impact

R S Stobie and P A Whitelock
South African Astronomical Observatory,
P O Box 9, Observatory, Cape 7935, South Africa
(email: rss@saao.ac.za paw@saao.ac.za)

1 Introduction

It is over one year since comet Shoemaker-Levy 9 (SL9) crashed into Jupiter. It was the first time in history that an impact between two major bodies in the solar system had been predicted in advance. As a result it led to the most intense observational campaign ever by amateur and professional astronomers alike. Every major observatory in the world was involved one way or another.

The model predictions of what would be observable varied from, at one extreme next to nothing, to at the other dramatic explosions and fireballs. As it turned out the latter predictions were much nearer the mark and the cosmic pyrotechnics were indeed spectacular.

This paper presents a brief and incomplete account of selected observational highlights and some of the early models developed to explain the observed phenomena. It concentrates particularly on observations from the optical and infrared spectral regions with an emphasis on results from the Galileo spacecraft, the Hubble Space Telescope (HST) and ground-based observatories, including the SAAO Sutherland outstation. It is almost certain that when the analysis and synthesis are complete we will have a somewhat different view of events than the one presented here. A description of observations at radio wavelengths is given by Smits (1996, these proceedings).

For further information readers are referred to the proceedings of two international conferences — the *European SL-9/Jupiter Workshop* (West & Böhnhardt, eds.) and *The Impacts of Comet D/Shoemaker-Levy 9 into Jupiter* (Noll, ed.). Other useful references that provide a qualitative picture of the event are Beatty & Goldman (1994), Chapman (1995), Beatty & Levy (1995), and Levy, Shoemaker & Shoemaker (1995).

2 Comet Shoemaker-Levy 9, Pre-Impact History

As one of the primitive bodies in the solar system, SL9 was born in an orbit probably beyond that of Neptune and of an age at least as old as the solar system (~10^9yrs). Possibly through encounters with the outer planets – Neptune, Uranus, Saturn and Jupiter – it suffered a progressive inward motion. About 10^3-10^4 yrs ago SL9 was injected into a short-period orbit inside that of Jupiter. About 66 years ago (~1929) SL9 was 'captured' by Jupiter into a 2-year orbit around the planet.

There is still controversy over the physical parameters of the comet prior to break-up and of the individual fragments. Most experts agree that the progenitor's diameter was at least 1.5 km. Thus, for a density of 0.5 g cm^{-3}, the total mass would have exceeded 10^{15} g. On 8 July 1992, at perijove, the comet passed Jupiter at a radial distance of ~ 100 000 km. As the planet has a radius of ~ 70 000 km, the comet passed only ~ 30 000 km above the cloud tops. As a result of the tidal stresses induced during this near encounter and the weak bonding of the comet, SL9 was torn apart (Fig. 1). The comet itself was not discovered until March 1993, by which time the fragments had separated sufficiently to give it the appearance of a 'string of pearls'.

As mentioned above the size of the progenitor comet (and hence of the individual fragments) is a major uncertainty with estimates for the diameter that have ranged from 1-10 km. The breakup of the comet and its subsequent appearance have been modelled successfully by Asphaug & Benz (1994) and Solem (1994). They both modelled the comet as a strengthless aggregate consisting of a large number of grains, and demonstrated that the tidally disrupted body rapidly condenses into clumps driven by self-gravity. Agreement with observation constrains the bulk density of the comet to be in the range 0.3-0.7 g

Papers presented at the 3rd ASSA Symposium

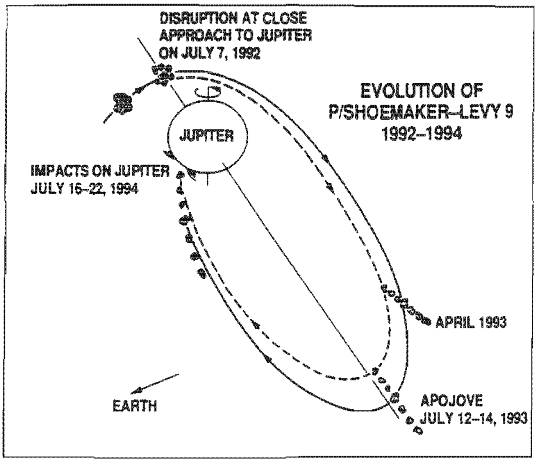


Figure 1. Schematic representation of the tidal breakup of the parent nucleus of comet SL9 in July 1992, the orbital evolution of its fragments, and their collision with Jupiter in July 1994 (Sekanina, Chodas & Yeomans 1994).

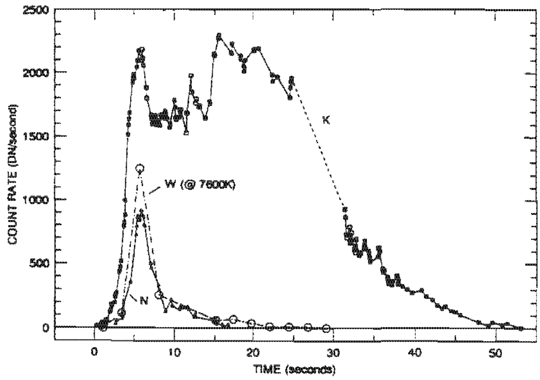


Figure 2. Galileo SSI light curves for the K, N and W impacts. The K and N impacts were observed through a narrow methane-band filter centred at 0.89 μm. The W impact was observed through a green filter (0.56 μm) and has been scaled to the others assuming a 7600 K black body. All large impacts observed had light curves similar to the K event (Chapman et al. 1995).

cm^{-3}, and a comet of diameter ~ 1.5 km. Thus after breakup the individual fragments are sub-km in size. Further support for small fragments comes from the dim entry flashes and fireballs observed at optical wavelengths by Galileo (cf Mac Low 1995).

These sizes contrast with the much larger fragments deduced by Weaver et al. (1994) and Sekanina (1995a, b). Their analysis of Hubble Space Telescope (HST) images was based on determining the nuclear magnitude, after subtracting the contribution of the coma light, and adopting a geometric albedo of 0.04. Their nuclear magnitudes imply nuclear diameters in the range ~ 2.5 to 4.3 km.

The physical breakup of the comet was complete within a few hours after perijove passage. By this stage the comet had coalesced into 10-12 major fragments with some high velocity particulates populating the dust trails far from the nuclear train. There is compelling evidence that secondary fragmentation occurred (cf evolution of the P-Q complex), indicative of the comet's continuing disintegration (Sekanina, Chodas & Yeomans 1994). The secondary fragments were smaller than the primary ones and led to condensations off the main train. In total 21 fragments were identified, denoted by the letters A to W (omitting I and O), and which would impact in alphabetical order. It is interesting to note that the condensations off the main train (fragments B, F, J, M, P, T) did not lead to major impact events. In addition, all fragments that 'disappeared' before impact were secondary fragments.

The 10-12 largest fragments contained ~ 90% of the mass of the progenitor (Sekanina 1995b). The dust clouds surrounding each fragment showed a strong peak in surface brightness, primarily due to the presence of an unresolved source – a nuclear fragment. The evidence is that, apart from secondary fragmentation, the main nuclei remained essentially intact until encountering the Jovian atmosphere in July 1994 (Sekanina 1995a).

There is some controversy on the origin of the dust in the comae which surrounded each fragment prior to impact. In particular, as to whether the comae were produced during the original comet breakup (e.g. Stüwe et al. 1995; Colas et al. 1995) or continuously after breakup (e.g. Sekanina 1995a). A few days before impact the larger fragments developed tails elongated in the direction of the planet (West et al. 1995) in addition to weaker tails pointing in the expected direction. No satisfactory explanation has yet been offered for this phenomenon.

Orbit calculations showed that over the period 16-22 July 1994 all 21 fragments would collide with Jupiter. The fragments would enter the Jovian atmosphere with a velocity of 60 km s^{-1}. The kinetic energy deposited by one fragment hitting Jupiter is $\frac{1}{2}mv^2$, where m is the mass of the fragment and v is its velocity. For a fragment of diameter 0.5 km, $m \sim 3 \times 10^{10}$ kg, and $v \sim 60$ km s^{-1}, the kinetic energy deposited is 5×10^{19} Joules (equivalent to 13 000 Mton TNT). A comparison with the energy released by the nuclear bomb that destroyed Hiroshima at the end of the second world war, ~ 0.015 Mton TNT, gives us some impression of the devastation which a comet impact on Earth could cause.

3 Impact Observations

All impacts occurred just behind the limb of Jupiter as viewed from Earth. Thus, neither ground-based telescopes nor the HST could observe them directly. Fortunately, however, the Galileo spacecraft had a direct line of sight to the impacts. This was of enormous value in interpreting the Earth-based observations and in getting the relative timing of the events. All attempts to observe the optical flash of the impact reflected from Jupiter's moons failed. In retrospect, knowing the energy of the flash as observed by Galileo, this result is not surprising.

Fig. 2 shows light curves for the K, N and W impacts (Chapman et al. 1995) from the Galileo Solid

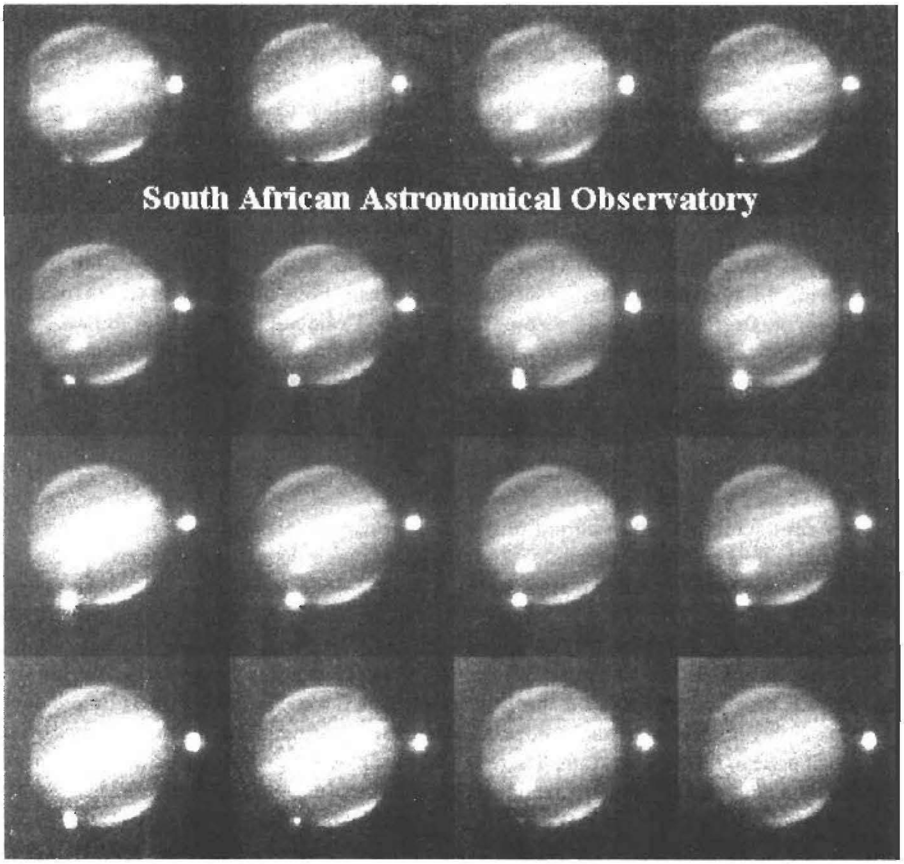


Figure 3. A montage of infrared images showing the impact of fragment A of comet SL9 with Jupiter on 16 July 1994. The images are 2.2 μm K-band images obtained with the the PtSi infrared camera on the 0.75-m telescope at Sutherland and taken at intervals of 1 min. The 'fireball' from the impact is visible on the lower left limb of Jupiter. The bright oval is the Great Red Spot and the moon Io is visible to the right of Jupiter. Note that the sequence starts at the bottom right corner and ends at the top left.

State Imager. These observations were obtained at wavelengths of 0.89 µm (K and N) and 0.5 µm (W). The very rapid initial rise in flux lasting ~ 5 - 6s is interpreted as the bolide (or meteor) phase of the fragment entering the Jovian atmosphere. All large fragments observed by Galileo (G, H, K, L) had light curves similar to K. The initial bolide phase runs into the emerging fireball phase. The 'plateau' lasting ~ 30s is caused by the compensating effects of the flux decreasing from the cooling fireball and the increase in the emitting volume caused by the expansion of the fireball.

The Earth-based observations provide a completely different perspective on the collisions from that of Galileo. Fig. 3 shows the results of the first impact, A, as observed at 2.2 µm from Sutherland with the 0.75-m telescope equipped with an infrared camera. The montage of frames, taken at one minute intervals, shows the development of the infrared splash-back (see below) following the fireball. This phenomenon lasted 13 to 14 minutes and its maximum brightness rivalled that of Jupiter's moon Io, also seen in these frames. The 2.2 µm filter was chosen by the Sutherland observers, in common with many other infrared observers, because of the Jovian methane absorption bands which dominate that spectral region. Jupiter is seen by reflected sunlight in the near-infrared as in the visible, but at 2.2 µm the methane absorption renders the reflection very inefficient. Thus any activity above the methane should stand out quite clearly. The contrast with the methane plus the characteristic temperature of the fireball and the splash-back are the primary reasons why the 2.2 µm pictures of the impacts are particularly clear. Infrared observations of some of the impacts showed precursor flashes a few minutes before the main event. Fig. 4 shows a preliminary reduction of the infrared (2.2 µm) light curve for the impact Q1 as observed with the SAAO 0.75-m telescope (Sekiguchi et al., in preparation). Although faint, a precursor was clearly recorded about six minutes before the start of the main event. The details of these precursors are discussed in the next section.

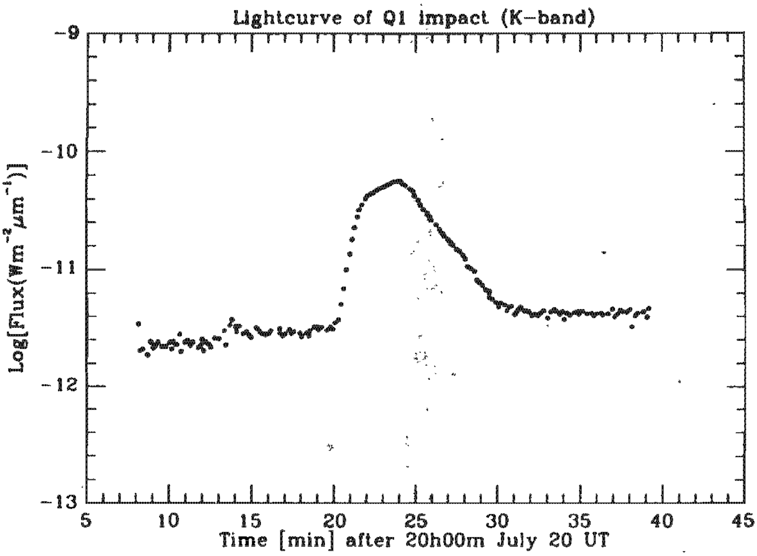


Figure 4. The 2.2 µm light curve for impact Q1 (preliminary reduction only) as observed with the 0.75-m telescope at SAAO (Sekiguchi et al., in preparation).

4. The Precursors and Timing of Events

Infrared precursors were observed with every sizeable impact and preceded the onset of the main infrared event by 5-6 min. (Herbst et al. 1995). However, observations with the most powerful telescope (Keck 10m) were needed to provide adequate time resolution of the finer details (Graham et al. 1995). As can be seen for impact R (Fig. 5, overleaf), there are 2 precursors which precede the rise to the main infrared peak by 5-6 mins. The detail shows that both precursors have a steep rise separated in time by ~ 60s.

To understand what is happening it is useful to relate the ground-based infrared observations to those made from Galileo. The relative timing of the events is shown in Fig. 6 on the next page.

Note that, while two precursors are seen in the ground-based measurements, the Galileo observations showed only one event. The gradual brightening in the infrared prior to precursor 1 is caused by increasing amounts of dust from the tail and coma of the

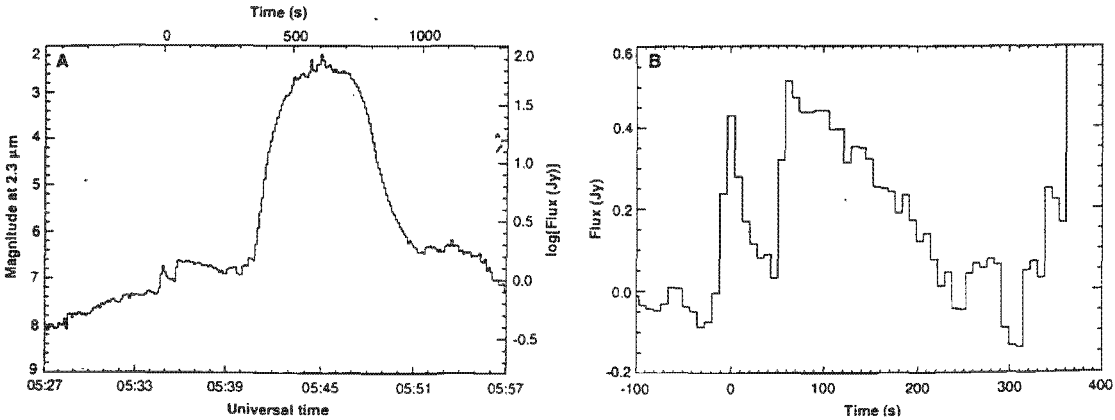
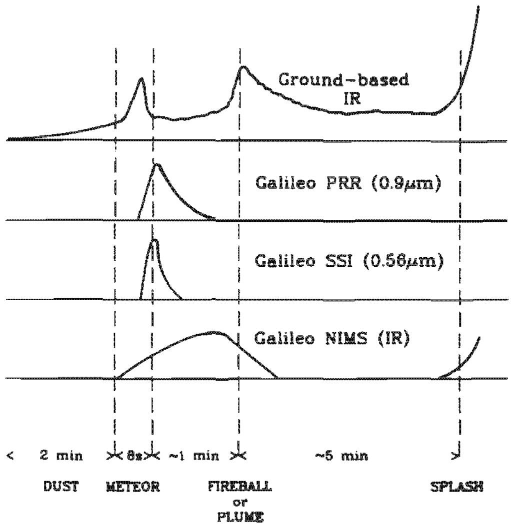


Figure 5 (top). Keck infrared (2.3 µm) observations of the light curve of the R impact. (a) The complete light curve as a function of UT; the time on the top axis is labelled in seconds from the peak of the first flash. (b) Detail of (a) showing the two precursor flashes (Graham et al. 1995).

Figure 6 (right). Schematic of relative timings of two precursors as observed in infrared by ground-based telescopes and by Galileo observations (adapted from Richard West, private communication).



fragment entering the Jovian atmosphere in advance of the fragment. The first precursor corresponds to the bolide phase of the fragment itself entering the upper atmosphere. Peak brightness occurs just before the fragment passes behind the limb of Jupiter (as seen from Earth) and thereafter precursor 1 declines in brightness. The initiation of precursor 2 is caused by the emerging fireball becoming visible above the limb of Jupiter. It declines in brightness as the fireball expands and cools. As far as Galileo is concerned, the bolide and fireball stages are continuously visible and indeed merge into each other, as there is no clear separation of events in the light curve.

We can check if these timings are consistent, following Nicholson et al. (1995) and Sekanina (1995c). Let $t_{\vee}$ be time of disappearance of meteor and $t_{\wedge}$ be time of appearance of fireball, both as seen from Earth. The corresponding heights above the 1 bar pressure level are defined as $Z_{\vee}$ and $Z_{\wedge}$ (Fig. 7). The Jovian atmosphere is transparent to tangential rays above a pressure of $p \sim 8$ µbar, corresponding to a height of 265 km (all heights are measured relative to 0 km at $p = 1$ bar). But the impact occurred $\theta = 4.9°$ behind the limb of Jupiter and thus $Z_{\vee} = R(1 - \cos\theta) + 265$ km. With $R = 69\ 000$ km then $Z_{\vee} = 517$ km. This height corresponds to $p \sim 1$ nbar and the frictional heating at this height implies a temperature T = 2400 K for the meteor fragment, consistent with the observations. Given that the fragment entered Jupiter's atmosphere with a speed of 60 km s^{-1} at an angle of 45° to the normal, then the vertical speed was 42 km s^{-1}. Assuming now that the fragment exploded at $p = 1$ bar then the meteor's flight time from when it became invisible to Earth to when it exploded was ~ 12s.

The fireball expanded along the path of least resistance, back up the 'channel' formed by the bolide. In determining its vertical component of velocity we note that the maximum height of fireballs as measured by the HST was $h \sim 3200$ km. To reach this height the vertical velocity of the ejecta must obey $v^2 = 2gh$, where g is Jovian gravity at 1 bar. With $g = 25$ m s^{-2} we obtain $v \sim 12.5$ km s^{-1}. (As this is the vertical component of the velocity and the angle of ejection is ~ 45° to the normal, the total velocity of ejection is ~ 18 km s^{-1}.) Because of Jupiter's rapid rotation, the fireball only needs to rise to a height $Z_\wedge = 480$ km for it to be visible to Earth. Thus the estimated rise time is ~ 38 s. Hence the total time between disappearance of meteor and appearance of fireball is $t_\wedge - t_v \sim 50$s. This is comparable to the observed $t_\wedge - t_v = 56$s for impact R, as shown in Fig. 7.

All the above calculation relates to the timing of the first and second precursors but tells us nothing about the main infrared peak, which remarkably was not predicted in advance by the models. It is clear now that the cause of the main event was thermal radiation from shock heating caused by the fallback of the ejected plume material. If v is the vertical velocity of the ejecta then the ballistic flight time of the plume is $t = 2v/g \sim 17$ min. This calculation assumes that the emission occurs when the ejecta fall back to the same level in the Jovian atmosphere as the fireball originated. In practice the dramatic brightening began ~ 5 min after the first precursor (when the impact region first rotated into view on the limb), reached its maximum in a further 5 min, and decayed over a period of a further 5 min. Predicting the exact time evolution of the observed flux is complicated by the simultaneously varying fallout zone and viewing geometries. Zahnle & Mac Low (1995), however, have shown that a simple, highly idealised model of a ballistic plume can produce the infrared light curve of the main event, similar to that observed (Figs. 4 and 5). Fitting the observations of the R impact they deduce that the R fragment had a diameter 450–500 m and a mass ~ 2–3 x 10^{13} g.

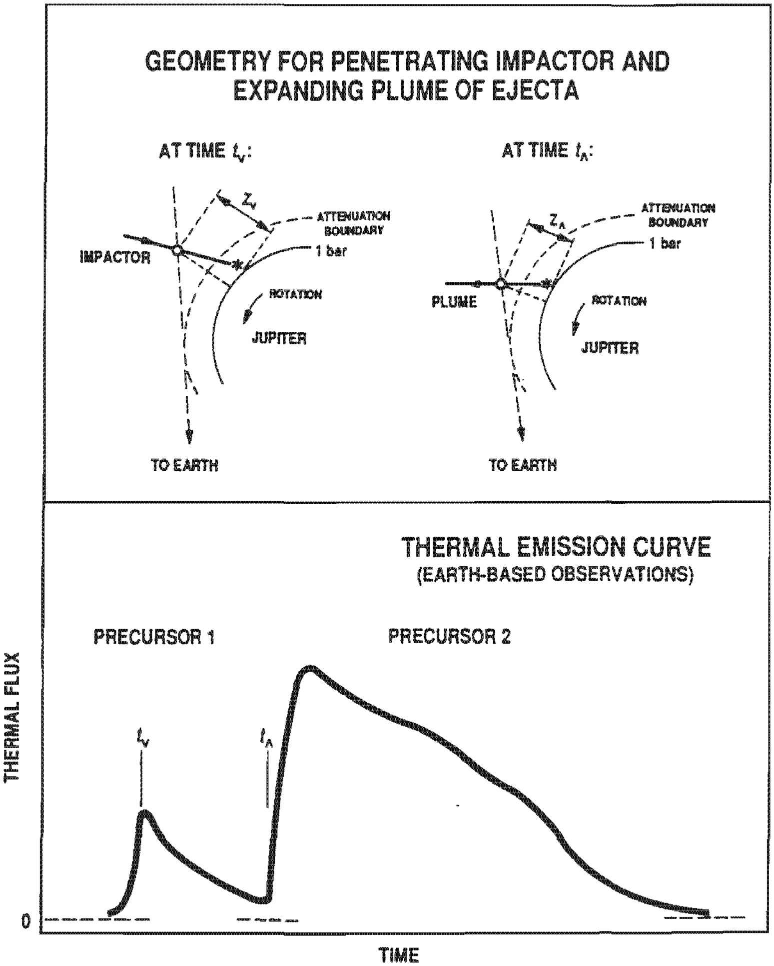


Figure 7. Geometry considered for an impactor penetrating the Jovian atmosphere and for an expanding plume of the ejecta (upper panel); and a schematic of the corresponding thermal emission curve as observed by a ground-based telescope (Sekanina 1995c).

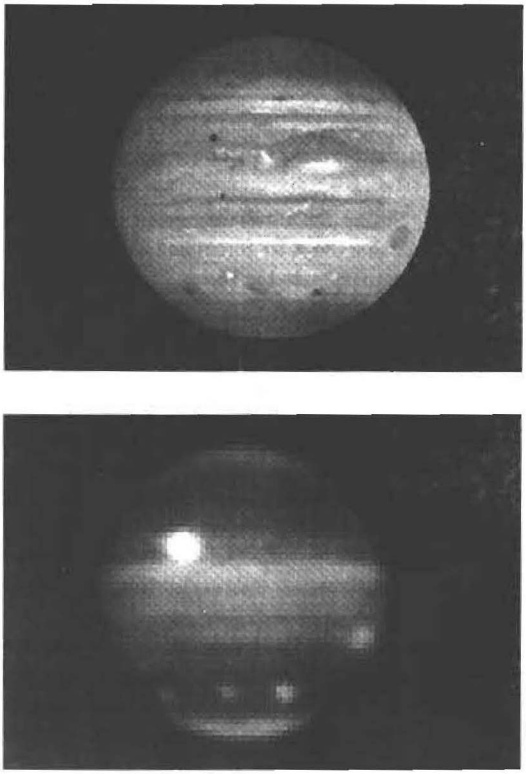


Figure 8. The impact 'scars' C, A and E as observed almost simultaneously by (a) the Hubble Space Telescope at 0.34 μm and (b) the 0.75-m telescope at Sutherland at 2.2 μm. Crossing Jupiter on its upper left is the moon Io, visible as a dark spot in the optical and as a bright spot in the infrared. On the right hand limb of Jupiter the Great Red Spot is visible as a dark feature in (a) and as a bright feature in (b).

5 The Meteor, Fireball and Splash Phases

The modelling of these phases in detail is complex. The actual penetration depth of the fragments is still uncertain. The depth of penetration depends on the size of the fragment, the bigger it is the deeper it goes, but it also depends on the ablation rate during the passage of bolide through the atmosphere. Both the fragment size and ablation rates remain unknown quantities. We do know, from the Galileo observations, that the fragments must have penetrated below the visible cloud deck. We also suspect, from the limited quantity of water observed, that it did not penetrate below the water cloud layer. It therefore seems likely that it exploded in the ammonia hydrosulphide layer or just above it, within the clouds of ammonia ice crystals, i.e. not far from the 1 bar pressure level.

The entering nucleus gets torn apart by the ram pressure of the bow shock. Fragmentation occurs because low-density, shocked gas decelerates the high density nucleus, causing the front of the nucleus to become Rayleigh-Taylor unstable. As the cross-section of the nucleus increases due to fragmentation, the energy gets transferred more efficiently to the atmosphere, the drag increases, eventually bringing the fragment to a rather abrupt halt accompanied by an explosive energy release. The result of this fragmentation is that the bolide is halted at higher altitudes than the early calculations indicated. Zahnle & Mac Low (1994) found that a km-size object of density 1 g cm^{-3} would explode at the ~ 10-bar level; if the density of the same sized object is reduced to 0.3 g cm^{-3} the explosion occurs at the ~ 2-bar level.

The detection of the impact by the Galileo photopolarimeter radiometer (PPR) began when the entering object expanded explosively at the altitude of peak energy deposition. As viewed from Earth, this occurred while the fireball was still behind the limb of Jupiter. The fireball was then observed by Galileo to rise, expand and cool adiabatically. By the time the observed fireball rises over the limb of Jupiter into sight from Earth, it had cooled enough to emit strongly in the near-infrared, but not in the visible, producing the second infrared precursor. The fragment G fireball, when first detected by the UV spectrometer and PPR on Galileo, was apparently 7 km in diameter with a temperature of at least 8000 K. Five seconds later the IR spectrometer detected it, and recorded the fireball's expansion, rise and cooling for 90 s, until it was hundreds of km across and only 400 K. In essence, the fireball as observed by Galileo resembled an expanding, cooling bubble of hot gas.

As the ballistic plume rose to its peak height, all its kinetic energy was converted into gravitational potential energy. Subsequently it fell, regaining kinetic energy until it hit the atmosphere at the same velocity it was ejected, converting its energy back to thermal energy in a shock wave. The strong infrared radiation of the main event carried away most of this energy, but not all of it – there could be a 'bounce'. If, however, the radiative cooling was effective enough to suppress the 'bounce', then strong (and easily observable) emission will be produced. Inadequate treatment of the radiative cooling was the fundamental error that prevented a clear prediction of the main infrared event from the models (Mac Low 1995).

6 The Impact 'Scars'

Fig. 8 shows the impact 'scars' of fragments C, A, and E observed almost simultaneously at optical wavelengths by the HST and at infrared wavelengths with the 0.75-m telescope and infrared camera at Sutherland. The moon Io is crossing in front of Jupiter. In the optical the scars and Io look dark, whereas in the infrared the scars and Io look bright relative to the planet. The scars are bright in the infrared, as discussed above, due to their position in the stratosphere above the methane. At visible wavelengths the methane is transparent and we see Jupiter by reflection from its various clouds and dominantly by reflection from the white ammonia ice crystals. The material in the ejecta which forms the scars reflects the sunlight much less efficiently than do the ammonia crystals. Its exact chemical composition is still uncertain but it contains aerosols and molecules rich in carbon and sulphur (e.g. Lellouch 1995). These scars again were features not predicted by the models and were noteworthy for their size, being easily visible with small telescopes (of size 6-inch).

Fig. 9 shows high-resolution detail of the G impact scar as observed by HST (Hammel et al. 1995). The small black spot (4) should be ignored as this is the impact site of fragment D which struck the previous day. The innermost dark spot (2) is the channel caused by the entry of the fragment into Jupiter's atmosphere and the subsequent exit of the fireball through the same channel. The time variation of the features reveals that the dark ring (1) is a propagating wave travelling outwards at 450 m s^{-1}. It cannot be an acoustic wave as the speed of sound at the relevant height in the Jovian atmosphere is ~ 770 m s^{-1} and it is thought to be a gravity wave trapped in a stable layer which acts as a horizontal wave guide. The visibility of the wave is probably caused by particles condensing and then being destroyed by evaporation as the wave moves past. It is interesting to note that the centre of this ring, which presumably is vertically aligned with the region of maximum explosive energy release, is not coincident with the channel (feature 2), because the fragment impacted at 45° to the cloud surface. The broad crescent-shaped feature (3) corresponds to the ejecta blanket, i.e. the resettling debris from the fireball. The distances of the inner and outer edges of the crescent-shape from

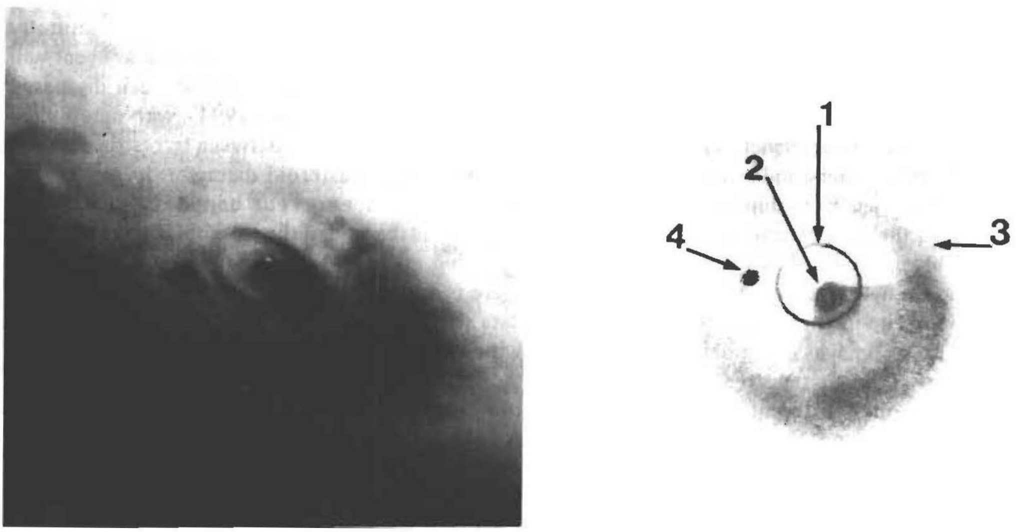


Figure 9. Detail of the G (and D) impact sites imaged with the HST Wide Field Planetary Camera 2, almost 2 hours after the G impact on 18 July 1994. The diameter of the circular ring is ~7000 km (Hammel et al. 1995). Note that the HST picture is as observed, while the sketch is corrected for projection effects.

the impact site are ~6000 km and ~13000 km, respectively. This feature is as large as the Great Red Spot and larger than the Earth. This crescent-shaped pattern can be modelled satisfactorily by fireball material following a ballistic trajectory with an initial speed of 15 km s^{-1}, zenith angle 45°, expansion speed of 2-5 km s^{-1} and under the acceleration due to gravity of 25 m s^{-1}.

The subsequent evolution of these 'scars' was determined by the strong differential winds in Jupiter as a function of latitude. As a result the 'scars' were rapidly smeared out in longitude in a band at Jovian latitude −44°, whose visibility lasted for almost one year.

7 Chemistry

The chemistry of the impact phenomena is extremely complicated and we are a long way from understanding it in any detail. Cometary molecules impacting at 60 km s^{-1} have a kinetic energy two orders of magnitude greater than their binding energy. Thus, not only will they be disassociated, but the excess energy of the fragments will be high enough to initiate several chemical reactions within Jupiter's atmosphere. In the shock (hot) chemistry which follows, all memory of the initial molecular composition of the impactor will be lost. A general review of the results to date is provided by Lellouch (1995).

Many molecules were detected in the atmosphere of Jupiter for the first time, or seen greatly enhanced, e.g., H_2O, S_2, CS_2 and HCN. All of the new or enhanced species were detected in the stratosphere or in the thermosphere of the planet. The bulk of the new material can be understood as originating from the comet, rather than from Jupiter. Early results which suggested that the detected mass of sulphur was considerably in excess of that which could have come from the Comet turned out to be incorrect.

At the time of the impacts there were also suggestions that no water was being detected. In fact the detection of H_2O was reported independently, after the event, from 5 different teams working at various wavelengths from the near-infrared to the radio. However, the presence of water still presents a problem for the models which suggest that most of the species produced should arise from the effects of shock-waves within the Jupiter/comet mixture. Under such circumstances SO_2 should be produced as well as H_2O. The fact that SO_2 was not detected may mean that the observed H_2O was actually cometary water that survived the explosion. This would be surprising given the energies associated with the impacts and subsequent explosions. The nature of the dark material in the impact scars is also unclear, but it seems to be comprised of aerosols or particles rather than molecules. C. N. Matthews has proposed that the dark material is a polymer of HCN (Levy et al. 1995).

8 Reflections on the Impact and Terrestrial Considerations

We have only touched on a small fraction of the observations and results concerning the Jupiter-SL9 impact. It is clear that the physics of the impact was complex. The results are still being digested and models improved to agree with the observations.

We indeed were privileged to witness such an event. Although such events must have been common in the early history of the solar system, it is apparent that, over the last 300 or so years during which Jupiter has been intensively observed, nothing like this has been seen (Hockey 1994). On the other hand crater chains on moons (e.g. Callisto, Ganymede and the Moon) have almost certainly been caused by similar events – a comet or asteroid tidally disrupted into a number of fragments impacting to leave a linear crater chain.

Having witnessed such an event, we naturally ask what is the probability that a similar event will happen to planet Earth? This has been discussed by Chapman & Morrison (1994), who determined the typical time interval between terrestrial impacts as a function of asteroid diameter. In general the probability of an event happening decreases strongly as the size of the asteroid increases. However, big events will still happen – it is just that there is a longer time interval between them. The data show that a 5m diameter asteroid will hit Earth with a typical time interval of 1 year. Events like the Tunguska explosion in 1908, caused by a comet of ~ 50m across, occur every few hundred years. An object 1 km in diameter (similar to an SL9 fragment), which could cause a substantial terrestrial catastrophe, is expected to occur every 100 thousand years. An event like that responsible for the Cretaceous/Tertiary boundary, when there was mass extinction of species (including dinosaurs), is expected to occur every 100 million years.