The comet collision with Jupiter: I. What happened in the impacts

John H. Rogers

Review article: a contribution of the Jupiter Section (Director: John H. Rogers)

In 1994 July, the 20-or-so fragments of Comet Shoemaker–Levy 9 hit the planet Jupiter. This article reviews the present understanding of the comet, the impacts themselves, and the chemicals they produced. The impacts of the 12 'on-line' fragments were spectacular in the infrared and left intensely dark smoke clouds. A typical large impact was detected first by infrared emission from the coma and nucleus entering the upper atmosphere, then as an optical flash visible to the *Galileo* spacecraft, then as a hot fireball or plume which rose over the limb and then collapsed to produce the infrared 'main event' by heating the stratosphere from above. Cometary and jovian molecules were dissociated in the heat of the fireball and splashback, and recombined to form new molecules, which may have been partially segregated according to their origin. However, more analysis will be needed in order to infer uniquely the mass and-composition of the cometary fragments. Large impacts had at least 10^{27} ergs (10^{17} kJ) and went at least to the 2-bar level, but may have been even larger and deeper.

Introduction

The comet impacts on Jupiter in 1994 July[1] generated a vast amount of data.[2,3] The impacts were not only more spectacular but also more complicated than most people expected, and the task of working out exactly what happened and where all the products came from is proving to be a lengthy one. This paper reviews the current understanding of the impacts achieved at several recent conferences. First was the AAS Division of Planetary Sciences in Bethesda, Maryland, USA on 1994 October 31, at which teams from many observatories displayed the detailed images, lightcurves and spectra which we had previously only heard about by e-mail.[4] Second was the ESO meeting at Garching bei München, Germany, in 1995 February 5. Third was the IAU Colloquium 156 at the Space Telescope Science Institute (STScI), Baltimore, Maryland, USA, in 1995 May; this meeting at last clarified the sequence of events during the impacts.

This article emphasises results given at the STScI colloquium. Excellent talks were given by many speakers but particular credit is due to Paul Chodas, Emmanuel Lellouch, and Gene Shoemaker, who presented magisterial roundups respectively of the impact timings, the chemical results, and the whole meeting.

The first rounds of reports on the impacts have been published in the ESO *Proceedings*,[5] in a special issue of *Science*[6] (the data from HST and Hawaiian infrared observatories), in special issues of *Geophysical Research Letters*,[7] and elsewhere.[8–13]

The relative magnitudes of the fragments and their impacts are listed in Table 1.

The orbit of the comet

SL9's orbit around Jupiter has been tracked back by at least three groups. All agree that SL9 was in orbit around Jupiter for many decades or even centuries, and the most likely capture date is 1929 (±6 yrs) – the year Carolyn Shoemaker was born! However it is impossible to be certain because the orbit is chaotic over that timescale; capture occurred through either the inner or outer Lagrange point, and even within the uncertainty in orbit of a single fragment (let alone the unknown centre of mass of the ensemble), one cannot be certain whether the comet slipped across the Lagrange point or not in a given year. Before capture, it was probably in a low-eccentricity, low-inclination solar orbit either between Jupiter and Saturn, or between Jupiter and Mars (with the 'quasi-Hilda asteroids'), like other comets that are known to have been temporary satellites of Jupiter.

Its orbit around Jupiter was near-polar, and maintained a period of 2–2½ years, but owing to solar perturbations, the orbit oscillated (with a period about twice that of Jupiter) between low and high eccentricity. Any comet trapped in such a polar orbit will undergo such oscillations and be at risk of colliding with the planet. High-eccentricity cycles brought SL9 very close to the planet in 1940–42, 1970, and (fatally) in 1992 and 1994.

Structure of the comet

The comet broke up during its close passage on 1992 July 7. Models of the tidal breakup have given a range of possible initial diameters, ranging from 1.5 km if it broke up at

Footnote

Abbreviations:

EIR, Earth-based infrared; GLL, *Galileo*; HST, Hubble Space Telescope.
GLL instruments: NIMS, Near-Infrared Mapping Spectrometer; PPR, Photopolarimeter-Radiometer; SSI, Solid State Imaging (camera); UVS, Ultraviolet Spectrometer.
EIR observatories: AAT, Anglo-Australian Telescope; ANU/MSSSO, Australian National University at Mt. Stromlo & Siding Spring Observatories; CFHT, Canada-France-Hawaii Telescope; ESO, European Southern Observatory; INT, Isaac Newton Telescope, Canary Is.; IRAM, Institut de Radio Astronomie Millimetrique, Spain; IRTF, NASA Infrared Telescope Facility, Hawaii; UKIRT, UK Infrared Telescope, Hawaii.

Definitions:

One bar is the mean atmospheric pressure at sea level on Earth. For the vertical scale of Jupiter's atmosphere, see Figure 9.

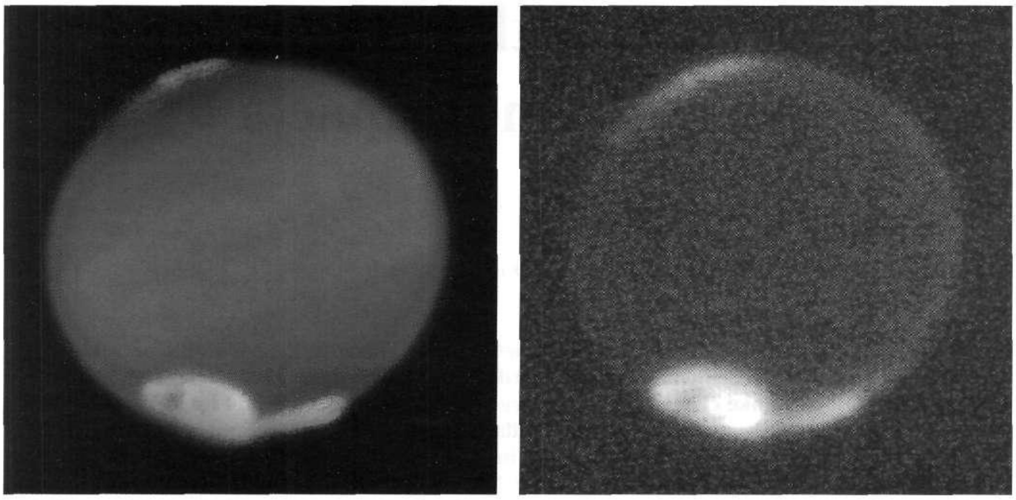


Figure 1. Impact G: the splash and aurorae, seen in emission at 3–4μm, from the ANU 2.3m telescope at Siding Spring.
Left: About 75 min after the impact, a huge ring of hot gas is centred on the impact site, 33,000km across – as large as the normal auroral areas (green). Note that the ring is larger than the visible impact site (Figure 2a). A similar ring was imaged for impacts C and K but not W. Colour coding is: blue, 3.09μm; green, 3.42μm; red, 3.99μm.
Right: A nearly simultaneous image at 3.28μm (July 18, 08h 50.5m) shows the huge ring, the normal aurorae, and a faint northern aurora opposite the impact plume (top left). A similar but brighter north conjugate aurora was imaged at 3.42μm during impact K; it coincided with the UV emission seen by HST (Figure 3). *(Peter McGregor & Mark Allen, ANU/MSSSO.)*

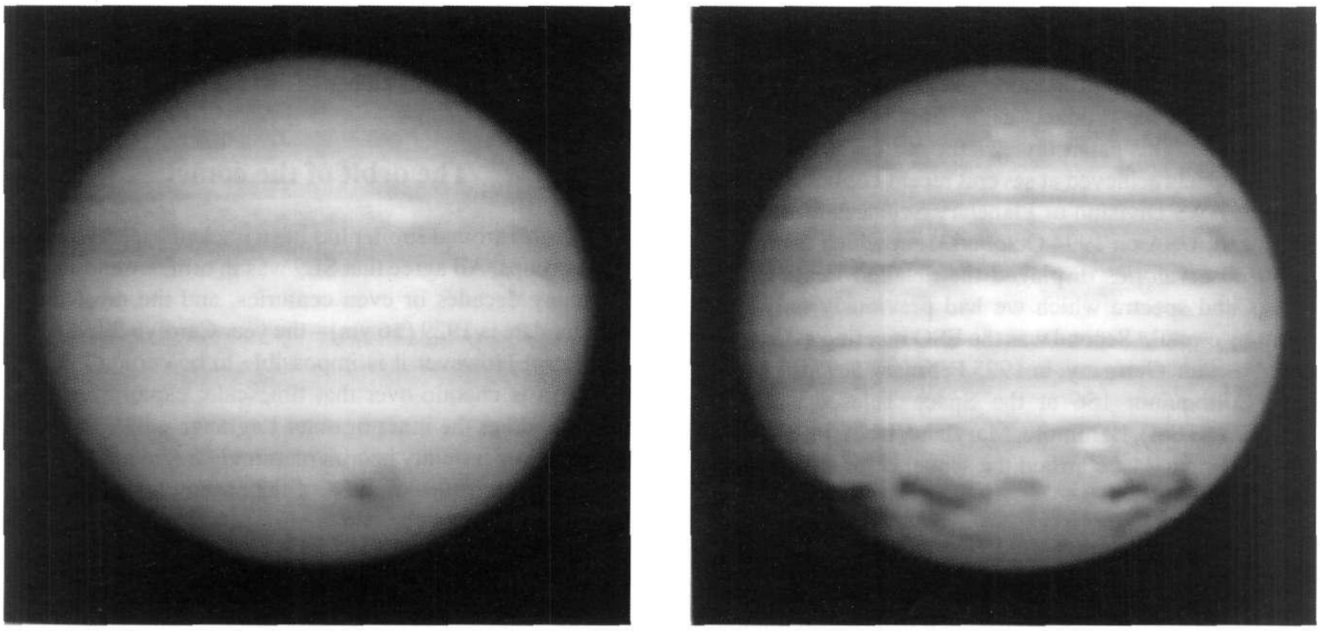


Figure 2. Visible-light CCD images of the greatest impact sites, on first passage and 9 days later, by Isao Miyazaki (40cm reflector, Okinawa, Japan). North is up.
Left: 1994 July 18, 10h 47m UT, ω_2 329°: site G, 3.5 hrs old, showing the classic core and crescent.
Right: 1994 July 27, 11h 01m UT, ω_2 248°: sites K, L, G (right to left), expanded and distorted by jovian winds.

perijove, to 9 km if it broke up 2½ hours later (which Zdenek Sekanina argues is most likely, from the position angle of the train of fragments).

Perhaps the best data on the mass of the fragments comes from the 8 crater chains on Callisto. These were described by Paul Schenk; they demonstrate that SL9 was typical of a class of objects that are tidally split by Jupiter every 150–200 years. The crater diameters indicate that the impacting fragments mostly had masses of 10^{14}–10^{15}g, equivalent to diameters of 0.4–0.8 km (assuming a density of 1 g/cm^3), with 6–25 such fragments per object.

Opinion has swung back and forth on whether the comet fragments were solid chunks (primordial building blocks) or loose swarms. Just before the impacts, E. Asphaug and W. Benz[19] showed by computer simulations that a loose rubble-pile comet, 1.5 km across with particles of density 0.5 g/cm^3, tidally disrupted like SL9, would re-aggregate very quickly by self-gravitation to form a string of pearls very like SL9. The first views of the actual impacts seemed to suggest the contrary – surely these were single point explosions! But it seems that the presently-accepted depths of the explosions (see below) could be achieved by re-aggregated rubble-piles just as well; on their way in they would elongate tidally but still be compact enough to be confined by a single shock wave. Likewise the Callisto crater-chains are ambiguous; the bowl-shaped floors of the

Table 1. Relative magnitudes of fragments and impacts

Fragment	*Magnitude*		
	Comet	*Fireball*	*Scar*
A	1.4	3	3b
B**	1.7	1b	1
C	2.1	3	3b
D	1.4	2	2
E	2.8	4	4
F**	2.1	0	0
G	4.1	5	5
H	3.1	4	4
K	3.8	5	5
L	3.5	5	5
N*	1.4	1ab	1
P2**	2.0	0	0
P1**	0.9	0	0
Q2*	3.1	1ab	1
Q1	4.1	4v	3a
R	2.5	4v	3a
S	2.9	4v	3x
T**	0.6	0	0x
U*	0.9	1?	0x
V*	1.4	1a	0x
W	2.4	4v	3x

Notes to Table 1

Comet: maximum diameters of nuclei (in km, upper limits) from HST image in 1994 May, from Weaver et al.[6] The nuclei were not distinguishable in these images, but their sizes were estimated by assuming a rather flat inner coma. Take the square to get estimated relative area and brightness, and take the cube to get estimated relative mass and kinetic energy. These relative magnitudes differ from those estimated from earlier HST images,[1] which included inner coma.

* These fragments were slightly (*) or obviously (**) off the main line, to the tailward side. These produced 'dud' impacts; in most cases there was some evidence of a faint flash at some wavelength, and/or a tiny scar imaged by HST, but they were far less than those of comparably bright on-line fragments.

Fireball: peak brightness of main event in infrared, estimated from 1 (very faint) to 5 (very bright). a: brief faint early flash; b: prolonged faint 'main event'; v: main event in these later impacts faded more rapidly than earlier ones.

Scar: size of dark spot formed, mainly from HST images, adapted from Hammel et al.[6]
Class 5: covers >10,000km, with Nf. core and Sp. crescent, and wave(s) if viewed on first passage.
Class 4: 4000–8000km, core & crescent & wave.
Class 3a: as 4 but less ejecta.
Class 3b: as 4 but core fainter and shorter-lived [JHR].
Classes 2 and 1: <3000 km, core only (± short streak to Sp.), no crescent, no wave.
Class 0: no scar visible.
x: These impacts were close to pre-existing scars which may have masked a weak fireball and scar.

craters are typical of single impacts, but rubble-piles could reaccrete quickly enough to produce this aspect.

At present, it seems that the Asphaug–Benz rubble-pile model can reproduce all the features of these events, just as well as the 'obvious', multiple-nuclei model. The Asphaug–Benz model is now more popular among workers in the field, but in the author's view this is only a matter of preference. Physicists are attracted by the model of a homogeneous substance which behaves in an ideal, calculable manner; conversely as a biologist, I find the 'obvious' picture of heterogeneous lumps more natural in the real world. (It also fits in nicely with the theory of cometary accretion in two phases, whereby condensation and collision produces primordial building blocks that then aggregate gravitationally.) In his summing up at STScI, Gene Shoemaker offered a compromise which might also attract some votes: that SL9 was made up of lumps with a continuous range of sizes, so some 'fragments' were dominated by single big lumps (with accreted smaller rubble around them), whereas others were only rubble-piles.

Another concept which has crumbled is that the SL9 fragments showed continuous cometary activity. No gas emission was ever detected, but there were persisting tails, and circular comae, and occasional secondary splitting, all of which were taken to imply cometary activity. Sekanina showed otherwise. The shapes of the tails and comae indicated that these were all debris from the 1992 breakup, just drifting at different speeds in the solar radiation pressure. The secondary nuclei (Q2, G2, the P family) showed no sign of being massive objects on impact, but also showed no effects of radiation pressure nor jetting before impact; in Sekanina's analysis, their orbits were purely gravitational (P split from Q at the start of 1993, and Q2 from Ql in spring 1993, with speeds of <l m/s). However he could not account for the fact that all the secondary and other 'wimp' fragments were displaced to the tailward side of the nuclear train. In the author's view, this suggests that they were subject to a non-gravitational cometary force away from the sun, but only briefly after they split off. If they were small but solid lumps, this might have been jetting from briefly-exposed ices; if they were films of tacky polymer, it might have been solar radiation pressure on a 'veil' which shortly crumpled. (There was no spectral evidence to distinguish these off-line wimps from the on-line nuclei; such minor colour differences as were reported did not correlate with the type of impact produced.)

However, the absence of detectable cometary activity does not imply that SL9 was an (ice-free) asteroid. A typical small comet might well show no detectable activity at that distance. Some people suggested that objects at that distance are likely to contain ices even if they look like asteroids. In any case, the hot water vapour observed in the fireballs probably came from the impactors (see below).

Regarding frequency, if 1.5km objects are split about once every 150–200 years because of passing through the Roche zone, then 1.5km objects will *hit* Jupiter every 500–1000 years, because the planet has a smaller cross-section than the Roche zone. Gene Shoemaker suggested frequencies slightly higher: one collision per 100 years (for a comet 1.5km across). But collisions by already-shattered comets like SL9 would be perhaps twenty times less frequent. From the absence of visual records of previous impacts, we know that the frequency is less than 1 in 80 years.

As the fragments neared Jupiter, by 1994 July 14, the comae elongated into long streaks, but the nuclei were still sharp and not much fainter than before. The comae elongated mainly towards Jupiter, so this was not merely due to gravity, but more likely due to the dust becoming charged in the magnetosphere and thus accelerated by Jupiter's magnetic field (D. L. Rabinowitz). The Hubble Faint Object Spectrograph comet team reported a strong Mg II emission from fragment G on July 14, which was only seen in the first observation after Earth occultation, but 18 minutes later the overall brightness of the nucleus increased threefold for several minutes, possibly the predicted effect of charging causing dust particles to explode.

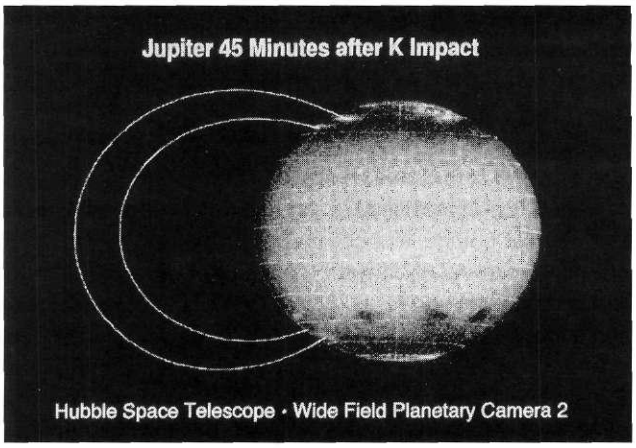


Figure 3. Ultraviolet aurorae just south of the K impact plume (near bottom) and at the equivalent point in the northern hemisphere (near top), 45 min after the K impact. HST image at 130–210nm. Magnetic field lines are drawn which link the novel aurorae; these lines go through Jupiter's radio-emitting radiation belts. Either particles or waves must have travelled along these lines to create the northern aurora. The K impact also produced northern-hemisphere auroral emission in X-ray and infrared wavebands (cf. Figure 1b). The normal northern aurora, nearer the pole, is also visible. Earlier impact sites (C, A, E) appear black. (North is up in this and all full-disk images.) *(John T. Clarke, University of Michigan, and NASA.)*

Effects on the magnetosphere and ionosphere

Although radio astronomers were disappointed by the absence of radio bursts coinciding with the impacts, there were several remarkable effects on Jupiter's magnetosphere and ionosphere. Early effects may have been due to the cometary dust particles becoming charged as they entered the magnetosphere, and thus distorting the usual electromagnetic patterns. Later effects may have been due to the fireball plasma sweeping the ionosphere southwards across Jupiter's magnetic field and thus inducing powerful currents, or due to the fireball shock wave pushing electrons into the radiation belts; none of the effects are uniquely explained so far.

(i) UV auroral emission near the south magnetic pole preceding the Q impacts, imaged by HST – the 'blinking aurora'.[6] This may have been due to the Q fragments on their way in, passing in and out of the magnetic polar cusp as the tilted magnetic field rotated.

(ii) X-ray auroral emission from the northern hemisphere, during the K and P2 impacts, imaged by ROSAT.[11] The first emission, a brilliant auroral spot, began sharply 3 minutes *before* the K impact, and was initially thought to be at the northern magnetic conjugate point (see Figure 3), but a reanalysis of the spacecraft pointing now indicates that it was some 90° away in longitude, near the northern foot of the Io flux tube. No-one yet has an explanation for this. A similar spot of strong emission occurred near the time of the dud P2 impact (which was otherwise undetectable), but seemed to be nearer the north pole.

(iii) UV auroral emission at the northern conjugate point, 45 min after the K impact, imaged by HST (Figure 3).[6] This image implied that either electrons or plasma waves travelled along the magnetic field lines from the expanding plume (south of the impact site) to the northern hemisphere. The K impact occurred at a longitude where the magnetic field shape is most favourable for such an effect to be observed, and produced this northern aurora at X-ray, UV, and IR wavelengths. (Weaker UV emission was seen near the K impact itself, both by HST and by IUE.)

(iv) IR auroral emission both from impact sites and from northern conjugate points, during and after impacts, observed in spectral scans from La Silla (ESO–NTT), Mauna Kea (UKIRT and IRTF) and Siding Spring (ANU). This is from H_3^+ ions, a normal marker of jovian aurorae, with emission lines between 3–4μm. Half an hour after the G and K impacts, the ANU 3–4μm images show a spectacular ring of emission at the impact sites, and also a spot at the northern conjugate point (Figure 1b), brightest for K. The other teams also saw strong emission from the plumes themselves and later, more diffuse emission from the northern hemisphere.

(v) Changes in the normal IR aurorae a few days after the end of the impact week, seen by the same teams. The main northern aurora was severalfold enhanced, while the southern aurora almost disappeared, possibly due to the impact debris spreading south to that latitude.

(vi) Decimetric radio emission from the radiation belts, increasing during impact week, recorded by several radio observatories.[13] The normally steady intensity increased by 10–40% at all wavelengths. It was initially confined to some longitude sectors, possibly due to the unevenness of Jupiter's magnetic field, but changing from day to day. After a few days the enhancement was uniform all round the planet and was slightly closer in than the normal radiation belts. It must be due to a change in the population of electrons. The enhancement violated expectations that cometary dust would suppress the normal radiation, and even more strangely, it has declined only at the longest (least energetic) wavelengths; 74cm emission was back to normal in early 1995 but 3.6cm emission was undiminished.

Dynamics of the impacts

There were three main sources of observations of the impacts themselves:

(i) Galileo (GLL), with a direct view.[1,7,12] All data have now been played back, including: 889nm (SSI) or 945nm (PPR) light-curves of L, H, K, N, Q1 (e.g. Figure 5b); UVS, PPR and NIMS spectra of G; NIMS spectra of R; visible images of W.

(ii) Hubble Space Telescope (HST) – imaging of 'plumes' rising over Jupiter's limb in visible or 889nm (methane) light,[1,6] with good sequences of A, E, G, W (Figure 4).

(iii) Earth-based infrared (EIR) observatories – from 0.89μm to 12μm, especially in methane bands, images and/or spectra of all the major impacts (e.g. Figure 5a).

The location of the impacts just over the limb was initially frustrating, both for visual observers who could not see them, and for EIR astronomers who found their complicated signals hard to interpret. However, the location turns out to have been perfect, given that *Galileo* could pinpoint the exact times of the impacts, EIR observers could record very faint phenomena on the dark limb, HST could image the rising plume in profile, and all observers could follow the fresh impact site during its first passage across the disk, which was ideal for study of its cooling, its chemistry, its wave phenomena, and its visual appearance.

The timecourse of the impacts was finally resolved at the STScI meeting. As the last of the *Galileo* data trickled back to Earth, a paradox had emerged: most of the large impacts were detected by EIR observers more than half a minute *before Galileo*. Worries that *Galileo* failed to see the bolide itself have now been laid to rest. The key points on the lightcurves can now be identified as in Table 2 (Figures 5 and 6). In summary, many of the EIR lightcurves showed a complicated pattern, whose main features were two 'precursor flashes' followed about 6 minutes later by the 'main event'. The first (t1) came just before *Galileo*'s detection, and represented the meteor entry; the second (t2) represented the upwelling fireball (plume). Then the EIR 'main event' erupted about 6 minutes later (t3), but this represented heating caused by the *collapse* of the plume.

The observations of impact G combine to provide a complete picture of one of the biggest impacts. GLL and HST observed this impact in greatest detail. The best EIR data, from Australia, were not well time-resolved but did include sensitive and detailed images (ANU/MSSSO, 30 sec exposures) and spectra (AAT, 1.5 sec exposures every few minutes) in the 2–4μm region.

The first EIR detection (t0) was a faint glowing spot in an ANU 2.3μm image exposed from 07h 32m 04–36s. As this was a minute before impact, it was probably the glow of a meteor storm caused by the incoming coma, burning up so high that it was in sight. Within the next minute (t1a) the spot brightened, presumably as the main fragment began its entry, and an EIR spectrum from the AAT at 07h 32m 58s, if thermal, implied a temperature hotter than 10,000°K.

At 07h 33m 32s (t1c), the *Galileo* UVS (at 292nm) and PPR (at 945nm) detected a flash – the final flaring and explosion of the main fragment. If this was thermal emission from a roughly circular area, the ratio of the intensities implies a temperature of 7600 (±600)°K and a diameter of ~8km. It was too cool to be seen in UV 5 seconds later, though it remained bright to the PPR and was first detected by NIMS in IR at that time. (The PPR continued to see it for ~30 sec; but a later revival reported by the PPR was probably not real.) NIMS spectra were taken over the next minute from 2 to 4μm and implied a temperature of ~4000°K over 10–20km diameter at t1c + 5 sec, cooling to ~1300°K over 85km diameter at t1c + 40 sec. This, then, was the expanding fireball, and these spectra also showed that it was rising; the effective level of the emission remained around 100 mbar for the first 20 sec (when it may have been dominated by the entry trail), then rose 30km higher over the next 20 sec.

At this time, the fireball rose high enough for EIR detection (t2) – a sharp increase in brightness around 07h 34m 43s (ANU). An AAT IR spectrum a minute later (07h 35m 50s) was still mostly hot continuum, though a long wavelength component had been added. (Likewise, Keck IR

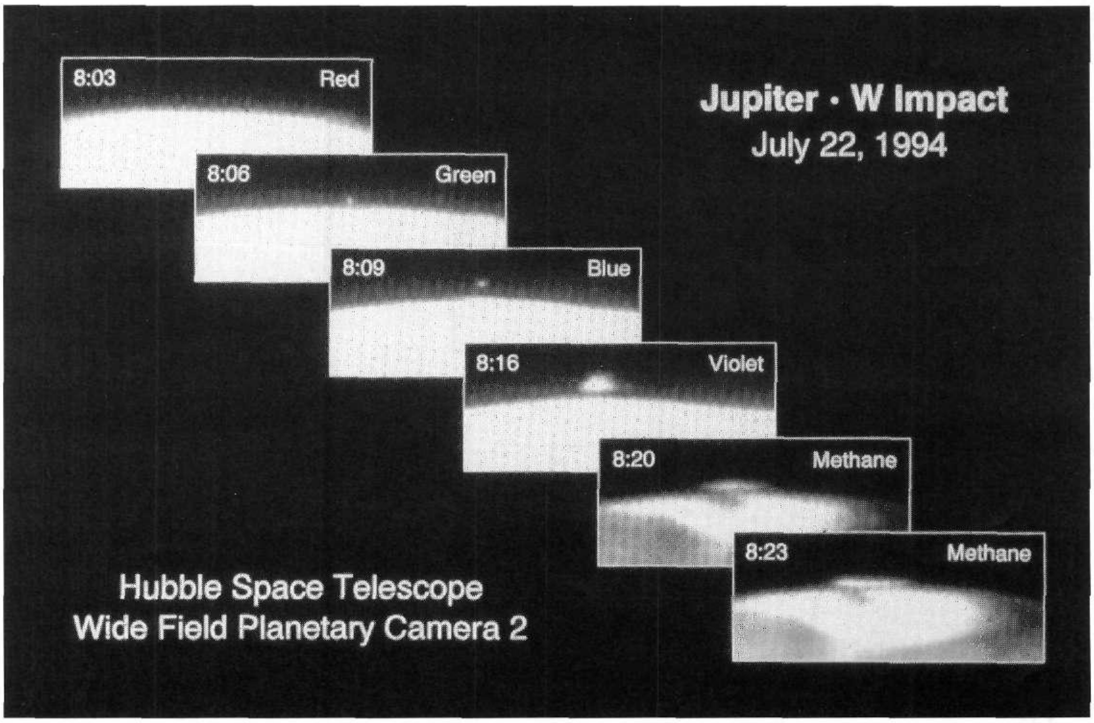


Figure 4. The W impact plume, rising over the pre-existing K impact site, seen from HST. Times and wavebands are marked.
8h 06m 16s: This 0.3-sec exposure shows a flash in Jupiter's shadow coincident with the impact flash photographed by *Galileo*. It is on the dark limb, projected 500km above the much-enhanced terminator.
8h 09m: Top of plume has risen into sunlight. Below it, a bright layer of site K catches the sunlight ~200km above the terminator.
8h 16m: Top of plume is near its greatest height, and the base is splashing and spreading into a pancake shape.
8h 20m, 23m: The pancake spreads to a diameter of 6000km, and is high enough to be sunlit ~500km above the terminator, well above the older, larger cloud of site K. *(HST Comet Team.)*

Table 2. Timecourse of observations of typical major impacts

Time	*(–t1c)*	*Lightcurve*	*Interpretation*
t0	–3 to –0.5 min	EIR, first detection	Coma meteor storm
t1a	–30 to –17 s	EIR, start of Pc1	Main nucleus enters atmosphere; start of meteor phase
t1b	–10 s	EIR, peak of Pc1	Main nucleus meteor disappears behind limb
t1c	0	GLL, first optical detection (UVS, PPR, SSI)	Main nucleus meteor brightening in troposphere
t1d	+2 to +5 s	GLL, optical peak and first IR (NIMS) detection	Impact: Terminal explosion and start of fireball/plume phase. (GLL optical and IR instruments record rising hot plume for next 10-40 sec as it rises and cools.)
t2	+50 s	EIR, start of Pc2*	Hot plume rises over limb.
t3	+6 min	EIR, start of main event	Start of splash phase, collapse of plume down onto stratosphere causing strong heating. (Main part is on or over the visible limb. EIR instruments record it for next 8-15 min, as it peaks at t1c + 10-13 min, then cools.)
t4	+20 min	EIR, 'bulge' (hiatus in decline of main event)	Bounce of plume on stratosphere?

Time symbols are defined in column 1. In column 2, typical times are given relative to the first Galileo detection, only approximately; t1b and t2 varied according to how far the impact was over the limb.
*Pc1, 'first precursor flash'; Pc2, 'second precursor flash'.

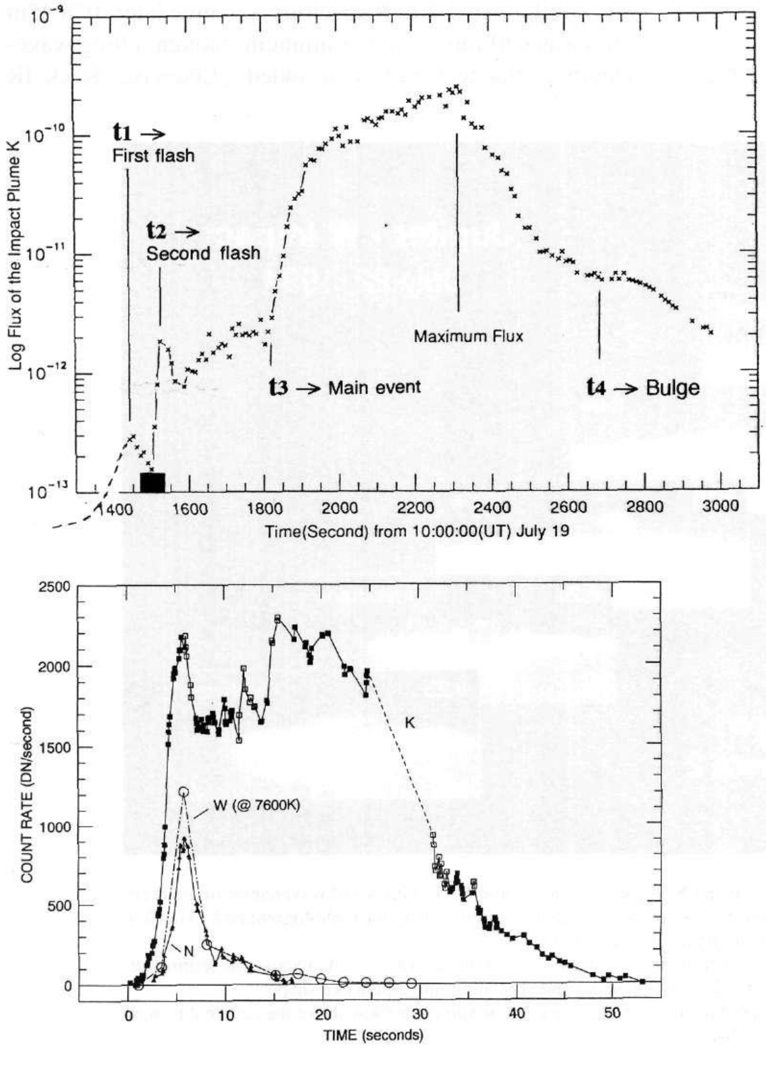


Figure 5. Typical EIR lightcurve (top) and GLL lightcurve (bottom), showing impact K.
Top: Lightcurve at 2.35μm from Okayama Astrophysical Observatory, adapted from ref. 14 with permission. The dashed line at bottom left indicates that a faint precursor spot was seen from Australia before the Japanese data commenced. The black box marks the period shown below.
Bottom: Galileo SSI lightcurves for K (at 890nm, methane band) compared with N (at 890nm) and W (at 560nm, scaled assuming temperature 7600°K). The sharp initial peak must be the bolide, followed by the fireball which was bright for K but barely perceptible for N and W. (*Galileo Imaging Team.*)

spectra of impact R showed the t2 flash to be cooler than the t1 flash.)

Thus *Galileo* saw the meteor followed directly by the expanding fireball. Remarkably, HST (889nm) imaged the initial flash also, faintly on the dark limb (image taken over 07h 33m 16–46s);[3,6] but the explosion seen by *Galileo* would not have been in its line of sight. Hubble may have seen the tail of the main meteor, or light from the explosion reflected off trailing coma dust. Subsequent HST images in visible light, from t2 onwards, showed the rising plume glowing over the dark limb, and by 07h 38m 16–31s, the top of the 'plume' was lit up by the Sun, even as the lower, shadowed portion still glowed feebly. Three minutes later the plume peaked at 3200km; then it collapsed (see below).

Meanwhile, the EIR 'main event' began at 07h 39m 30–41s and peaked about 07h 46m. This was inaccurately called the plume or fireball at first, and later renamed the hypervelocity splat; now it is designated the splashback. The infrared spectra showed temperatures increasing from a few hundred to over 1000°K. After t1c + 10–12 min, the AAT spectra became dominated by emission from newly created carbon monoxide at ~2500°K, over the persisting ~460°K thermal emission. This splashback emission was very high in the stratosphere, around the 10 μbar level.

The timecourse of this splashback indicates the vertical speeds at which the fireball erupted. Material ejected and re-entering at 4–5 km/s initiated the splashback at t1c + 6 min, whereas material at 12 km/s reached the maximum altitude of 3200km and re-entered later and hotter.

The G event provides a paradigm for all the impacts, in terms of both GLL, HST, and EIR data. The observed timings are listed in Table 3.

The *Galileo* PPR and/or SSI gave similar light-curves for all impacts observed: L (the brightest), K, H, Q1, W and even N (a near-dud) (Figure 5b). The brightness of the initial flash, lasting a few seconds, varied by less than a factor of 3 between the impacts, (1–4% as bright as Jupiter in continuum light) probably because this meteor luminosity scaled with the diameter, not the mass, of the fragment. The main differences were in the second phase (the expanding fireball) which remained near the peak brightness for 30–40 seconds for K and L, but trailed off much more rapidly for others.

In HST images, the four impacts directly observed (A,E,G,W) were also very similar in spite of their different energies, and all four plumes rose to nearly the same maximum altitude of 3000km (±300km) around t3 [compare the image sequences of G (ref.3) and W (Figure 4)]. There were some differences: G, the most energetic plume, was somewhat broader and slower-rising than the others. Later, at t1c + 12–15 min while the EIR main event was brightest, HST saw the whole plume collapse and broaden, precisely on the visible limb, increasing its diameter two- to four-fold as it skidded across the stratosphere. This area then emerged as the visibly dark area (Figure 2a.) The dark crescent, on the s. and p. sides, represented the outermost part of the plume. If its position angle of about 35° was due to Coriolis force acting during the splashdown, as the HST team suggest, it continued to skid outwards for 45 minutes after impact. The black core represents the site of the main explosion.

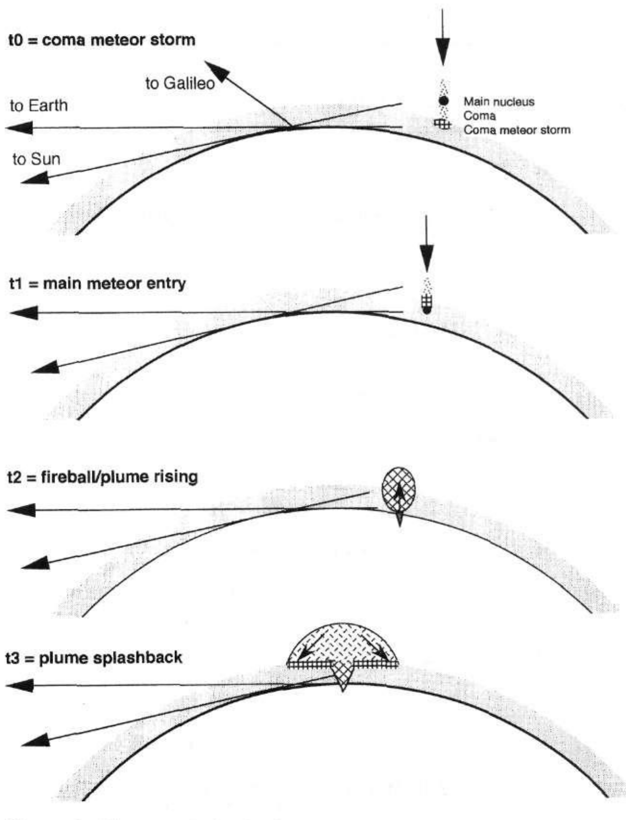


Figure 6. Diagram of the viewing geometry during the stages of a typical impact.

In EIR data, all major impacts showed one or both 'precursor flashes' before the main event. The Keck image sequence of impact R[3,6] is one of the best and the second flash is possibly resolved as a plume projecting southwards above the limb, firing back along the entry track. The Pic du Midi obtained a similar sequence for H. For some impacts (H and K) there was a prolonged 'pre-precursor' (t0), and t1 and t2 were more like steps than flashes, and the t3 rise was rather gradual, suggesting a large amount of coma rubble surrounding the main fragment. For earlier impacts A to D, which were further over the limb, the single EIR flash observed seems likely to have been the t2 flash at t1c + 1.5 min, as the t2 flash was generally brighter. But for some of the later but fainter impacts, the brief flashes seen by GLL (N) or EIR (Q2, V) were probably t1 flashes, due to a bright meteor phase which produced little or no fireball; their delayed splashback emission was weak (N, Q2) or absent (V). (In later HST images, the impact sites of N and Q2, and of B, were tiny 'pinprick' dark spots with no visible ejecta; site V was not detected as V went into previous site E.)

Impact L was the brightest impact, in GLL and EIR data, and was very well observed from the Canary Islands. The plume was actually imaged in near-IR and visible light during the 'main event' (Figure 7a), partly because it was sunlit (as in HST images), but also because of line emission from metal atoms (as in terrestrial meteor spectra; see below).

The EIR 'main event' or splashback always started about 6 minutes after the impact, reaching 2000–3000°K, though the bulk of the emission may have been from condensed particles at 600–1000°K (ref. 7b). It seems that a substantial fraction of the initial input energy went into raising the

Table 3. Times of impacts and plumes

		T = t1c = 'accepted time'	t0/t1a = first flash onset	t2 = second flash onset	t3 = main event onset
A	16d	20:12 (±1m) c	20:11:29 (5) CA	*20:13:23 (7) HST*	20:16:56 (5) CA
B	17d	02:50 (±3m) b	02:50: (±) UKIRT[H3+]	--	02:56: (±) Keck
C		07:11 (±1m) a	--	07:11:57 (15) AAT (& ANU) 07:12:07 (5) Oka	07:16:45 (15) AAT (& ANU, IRTF) 07:16:30 (30) Oka
D		11:53 (±1m) a	--	11:54:30 (30) ANU	11:58:30 (30) ANU 12.00.14 (8) Oka
E		15:12 (±2m) c	--	--	15:17:56 (5) CA (& SPIREX)
F	18d	00:37 (±7m) o	--	--	--
G		07:33:32 (GLL)	07:32:20 (30) ANU *07.33.31 (15) HST*	07:34:43 (30) ANU *07:33:37 (3) GLL-NIMS*	07:39:30 (30) ANU *07:39:41 (3) GLL-NIMS*
H		19:31:59 (GLL)	t0 ≈ 19:29: (±) CA t1a= 19:31:38 (3) Pic (& CA) t1b= 19:31:46 (4) Pic (& CA)	19:32:30 (1) CA (& SPIREX) 19:32:41 (2) Pic (& CA) 19.32.57 ESO[10 μm]	19:37:30 (1) CA[3 μm] 19:37:25 (2) Pic (& CA)
K	19d	10:24:13 (GLL)	t0 = 10:20:41 (30) ANU t0 = 10:22:42 (40) AAT t1a= 10:23:03 (30) ANU t1a= 10:23:19 (40) AAT t1b= 10:24:03 (5) Oka	10:25:24 (30) ANU 10:25:03 (5) Oka	10:30:30 (30) ANU (& AAT) 10:30:23 (5) Oka
L		22:16:48 (GLL)	t1a= 22:16:18 (3) CA * t1b= 22:16:41 (3) CA	22:17:27 (3) CA (& Pic)	22:22:40 (18) Pic (& CA)
N	20d	10:29:17 (GLL)	--	--	10:35:40 (30) ANU
P2		15:23 (±7m) o	--	--	--
Q2		19:44 (±1m) b	19:44:10 (1) CA[3 μm] (& Pic) 19:44:47 (3) CA	--	19:52:10 (1) CA
Q1		20:13:52 (GLL)	t0 = 20:09:50 (1) CA t1a= 20:13:15 (1) CA (& Pic) t1b= 20:13:40 (1) CA	--	20:19:15 (1) CA[3 μm] (& Pic) 20:19:47 (3) CA (& SPIREX)
R	21d	05:35:03 (d)	t0 = 05:33:56 (5) McD t1a= 05:34:44 (8) Keck (& Pal) t1b= 05:34:52 (10) Keck,Pal	*05:35:08 (3) GLL-NIMS* 05:35:27 (10) Pal 05:35:46 (8) Keck	05:40:00 (30) ANU 05:38:34 (30) Pal[3 μm] 05:40:57 (8) Keck
S		15:16 (±2m) b	--	15:16:00 (30) SAAO	15.22:00 (30) SAAO
T		18:11 (±7m) o	--	--	--
U		21:56 (±7m) o	--	--	22:00:37 (±) McD (& CA)
V	22d	04:23 (±1m) b	04:23:09 (10) Pal (& AAT)	--	--
W		08:06:14 (GLL)	*08:06:16 (1) HST*	08:06:24 (30) ANU	08:12:00 (30) ANU

Notes to Table 3:

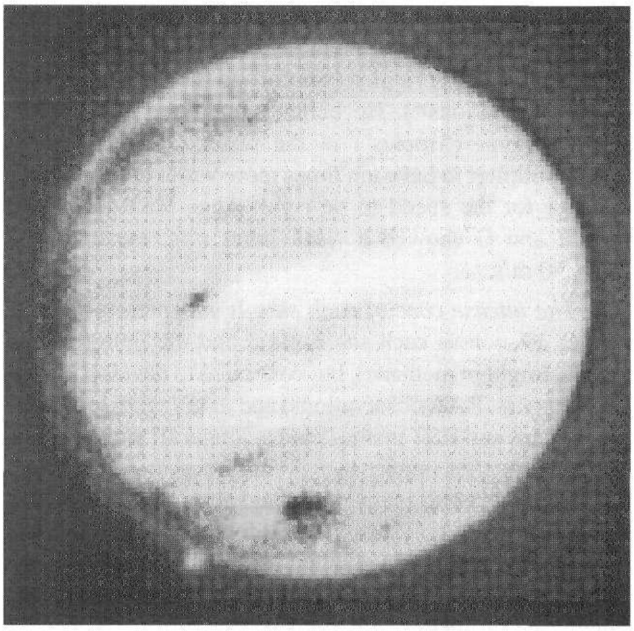
This table is adapted from the near-final compilation by Paul Chodas and Don Yeomans dated 1995 July 13, by courtesy of Paul Chodas. It supercedes earlier versions given in BAA Circular 740 and a Jupiter Section Circular. Not all data are listed, only those which best define the onset times.

Column T: Best estimate of time of impact, UT (hr:min:sec). Determined as follows: GLL: taken as time of first Galileo detection in optical or near-IR (t1c, mostly ±1 s). a: taken as 1 minute before first IR flash; b: taken as coincident with IR flash; c: estimate from orbit (±7 min) and Hubble $\lambda 3$ (±4 min) and IR main event (–6 min); d: taken as 5 sec before Galileo NIMS detection, by analogy with impact G. o: from orbit only (±7 min).

Columns t1,t2,t3: Observed Earth-based infrared timings, as defined in Table 2. Times are UT, with uncertainty in seconds given in brackets. Other observatories listed in brackets gave less precise timings which agreed with the one listed.
Where only one 'precursor flash' was detected it may be uncertain whether it was t1 or t2. For earlier impacts which were too far over the limb, the one observed was probably t2 as it was generally brighter; but for later, smaller impacts, if only one precursor flash was observed it was probably t1 (meteor), the fireball and main event being weaker (cf. GLL lightcurve of N).
Observatories are: AAT = Anglo-Australian Telescope; ANU = Australian National University at Mt. Stromlo; CA = Calar Alto; ESO = La Silla; GLL-NIMS = Galileo infrared spectrometer; McD = McDonald; Oka = Okayama; Pic = Pic du Midi; Pal = Mt. Palomar. Wavelengths are mostly 2.0-2.3 μm unless otherwise stated. The plume (t2) and spashback (t3) sometimes appeared earlier at longer wavelengths. Also, in italics, some timings from HST images.

The table does not include times of reported flashes from Io; these were probably noise, because they did not bear any consistent relation to other impact timings, and the optical flashes seen by Galileo were too weak to give detectable flashes on Io. Also omitted are most times from the AAT, which were ±3 min due to the cycle time for spectrograms.

* Calar Alto reported faint IR spot visible for ≥18m before L impact, probably from an unknown minor impact.



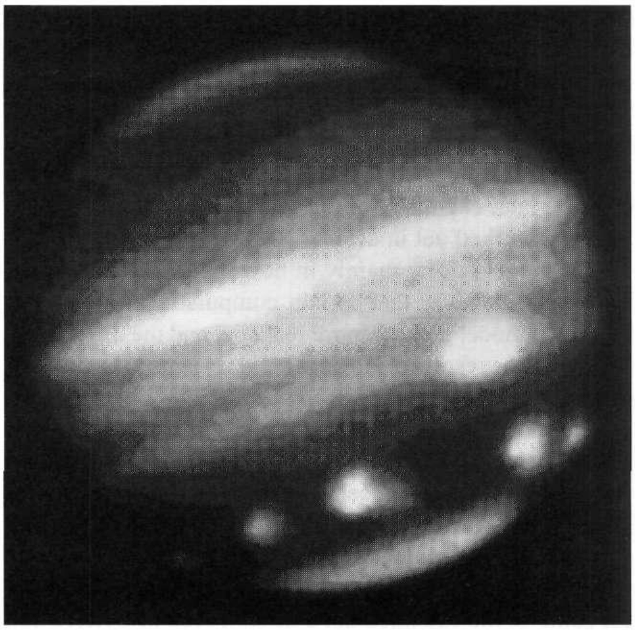


Figure 7. Impact L, which was one of the brightest. North is up.
Left: The plume in near-infrared light (907nm) from the Jacobus Kapteyn telescope on La Palma. This image was taken at 22h 26m, 9m 15s after the *Galileo* detection of impact L. The limb region has been enhanced to show the faint plume, shining probably by reflected sunlight (as in the HST images), a minute before metal line emission was first detected. To the right, older site K appears dark on the disk. *(Dr Peter Andrews, Royal Greenwich Observatory.)*
Right: A nearly simultaneous image at 2.16μm from the Pic du Midi, showing the 'main event' – thermal emission from splashback of the plume. To the right, site K appears bright due to sunlight reflected off its high-altitude smoke cloud, with sites C and A further round. *(F. Colas, J. Lecacheux, D. Tiphene, & D. Rouan; from ref. 7a.)*

plume and most of this went into heat in the splashback. (A similar effect has been proposed for Earth after the K/T impact: the ejecta re-entering the atmosphere as a vast meteor storm may have produced enough heat to burn the world's forests.) For the later impacts, the main event was bright but shorter. This may be partly because these plumes came further over the limb, but there were also real differences; R and W showed less hot CO and water emission, and produced less visible ejecta, than earlier impacts. Conversely, early impacts A and C produced conspicuous ejecta but rather weak cores.

Some of the EIR light-curves showed a broad fourth peak, starting 20 minutes after impact. This may represent the plume bouncing on the stratosphere, as appears in some of the models (below). In fact the Palomar light-curve of impact R showed yet another slight peak 20 minutes later, consistent with bouncing.

How massive were the fragments and how deep did they go?

It still appears likely that the plumes came from a level in or below the putative NH_4SH (ammonium hydrosulphide) cloud layer (at 2 bars pressure) but above the putative water cloud (at 4–6 bars pressure) (see Figure 9). The main evidence for the level is the HST UV spectra of the core of the impact site, showing abundant sulphur and its compounds, but not SO_2 (see below). This chemistry indicates a very high S-to-O ratio – and Jupiter's NH_4SH cloud layer is just about the only place in the solar system where such a ratio might reasonably be found.

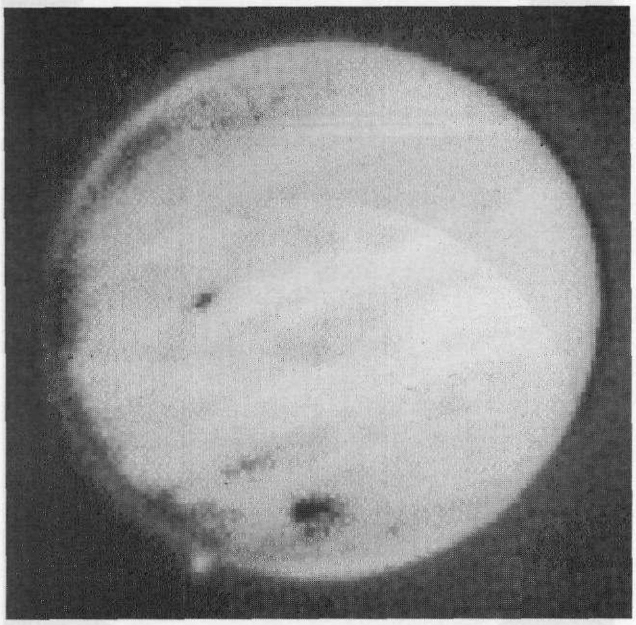
However, two classes of model with very different penetration depths can both reproduce the observed phenomena. It does not seem to make much difference if the impactor is larger and goes deeper, as the extra energy is swallowed up in Jupiter.

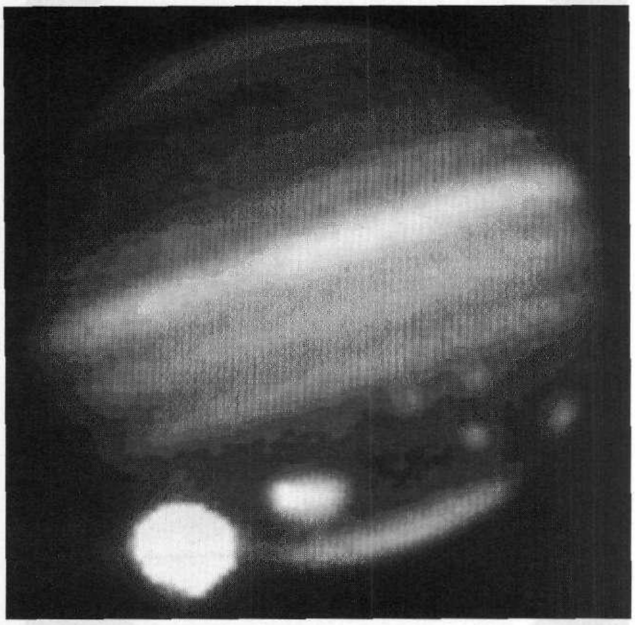
One model with moderately small, moderately deep impacts was presented by Mordecai Mac Low and Kevin Zahnle.[15] In their model, the larger fragments comprised about 10^{14}g (10^{27} ergs) and went only ~60km below the cloud tops to explode at ~2 bars pressure, in the NH_4SH cloud layer. This corresponds to a lump of diameter 0.5km at 1 g/cm^3, or an Asphaug–Benz rubble-pile of 0.7km at 0.5 g/cm^3, entirely consistent with the various tidal breakup models. According to Zahnle, most of the comet's mass and almost half its energy goes into the plume and thence into the splash. The model nicely accounts for the fixed height of the plumes; although a more massive fragment penetrates deeper, the fireball has to push against a larger mass of jovian 'air', which equalises the plume height.

Conversely, models by T. Takata, T. Ahrens et al.,[16] and by David Crawford and Mark Boslough of Sandia Labs,[17] have much deeper penetration with fragments of 2–3km diameter going several hundred km below the cloud tops. The Sandia Labs model is most highly developed. A fireball starts to appear immediately, as observed by *Galileo*, because as soon as the bolide begins to dump some mass and energy along on its trajectory, the explosion starts at that point. The upper part of the fireball is boosted by the continuous 'line explosion' growing beneath it. But most of the mass and energy goes deep and stays deep. The troposphere/ stratosphere boundary, which is the coldest atmospheric level, acts as a choke point so material from below here (including jovian water and most of the comet) mostly does not get into the plume. However, these models do not naturally account for the invariant plume height; for deep penetrators, the plume height depends on the diameter of

Correction – Paper I

We regret that a wrong image was used for Figure 7B of Paper I of this series, 'The comet collision with Jupiter: I. What happened in the impacts' (*J. Brit. Astron. Assoc.*, **106**(2), 69 (1996 April)). Both parts of the correct figure are reproduced below.





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the impactor, so to achieve a 3000km plume, these models have to propose that all the fragments were about 2km across but of varying density.

(Eventually, the deep track with hot cometary material should convect up to the surface in the hour following the impact, revealing itself in the 'bump' on the EIR lightcurve or in the later chemistry of the core, but this aspect has not yet been worked out in detail.)

The models differ mainly in how the bolide breaks up. Each team believes that certain computational aspects of their own model make it more realistic, and the differences have yet to be resolved. However, there seems to be no positive evidence in favour of deep penetration.

The modellers generally agree on the dynamics of the plume, which achieves very much the timecourse and temperatures that have been inferred from the observations (see below), including the skidding and bouncing after splashback. The plume is surrounded by a rarefied shock wave which expands extremely fast and this may account for some of the extended hot emission seen in UKIRT and ANU 3–4μm data.

Development of the impact sites: waves and thermal effects

(i) The spectacular great ring imaged at 3–4μm in the first 2 hr after the largest impacts, by the ANU/MSSSO, described by Peter McGregor (Figure 1). The ring radius was 5000km at t1 + 40 min, as it came over the limb, and 15,000km by t1 + 75 min, so the ring was actually outside the visually dark crescent (outer radius 13,000km for site G). In the following hours, it did not expand further but faded away. This ring may be emission from hot methane and/or H_3^+ above the stratosphere, and it may represent the outermost part of the splashback or skidding of the plume.

(ii) The small, narrow ring seen in the first HST image of site G – dark brown in the visible, bright in methane, like all impact ejecta. A similar ring was seen in several sites by HST on their first passage, viz, A, E, G, Ql, R. All the observations fitted a uniform ring expansion rate of 450 m/s. According to A. Ingersoll,[9] this is too slow for sound waves, or for stratospheric ripples (contrary to the the well-known colour simulations[18]). He believes they are tropospheric gravity waves ('ripples') in the water cloud layer, but requires Jupiter to have ten times more water than expected in order for the speed to be right. Also, HST images of sites E and G showed a weak inner ring, expanding at 270–350 m/s.

(iii) The intense core of each site: It was present in HST images as soon as each site came round the limb (dark in visible, bright in methane), but continued to develop in visible light (e.g., BAA observations) and in UV (IUE low-resolution scans and HST images) and at longer IR wavelengths. Three hours after impact L, Palomar images around 10μm (emission related to temperature and ammonia abundance) showed the core only just starting to appear, although the ejecta crescent had been glowing for hours; and at 7.8μm the ejecta crescent glowed (emission from methane in the stratosphere; see (iv) below) but there was no core at all.

It seems to be generally agreed that the core represents not only the dying gasp of the explosion, but also a 'depot injection' at the explosion site which continues to convect upwards for days after the impact. E.g., spectra at 2.2μm from Cerro Tololo showed that the black core of site E was deeper in the stratosphere than its ejecta crescent, when 11 hours old (and see below). Reta Beebe's analysis of HST images over several days suggested anticyclonic spiralling of dark smoke from cores L and Q1, also consistent with a warm rising column, although other sites showed diverse motions.

(iv) Heating of the atmosphere: After the first hour or so, the impact sites were no longer glowing at wavelengths less than 7μm; the bright spots in EIR images were due to sunlight reflected off the debris clouds. However, persistent heating at various levels has been inferred from EIR spectra in various molecular bands, in sites of various ages (Table 4). Although these estimates are still approximate and the area affected is not always known, they confirm that the heating was strongest on top of the stratosphere due to

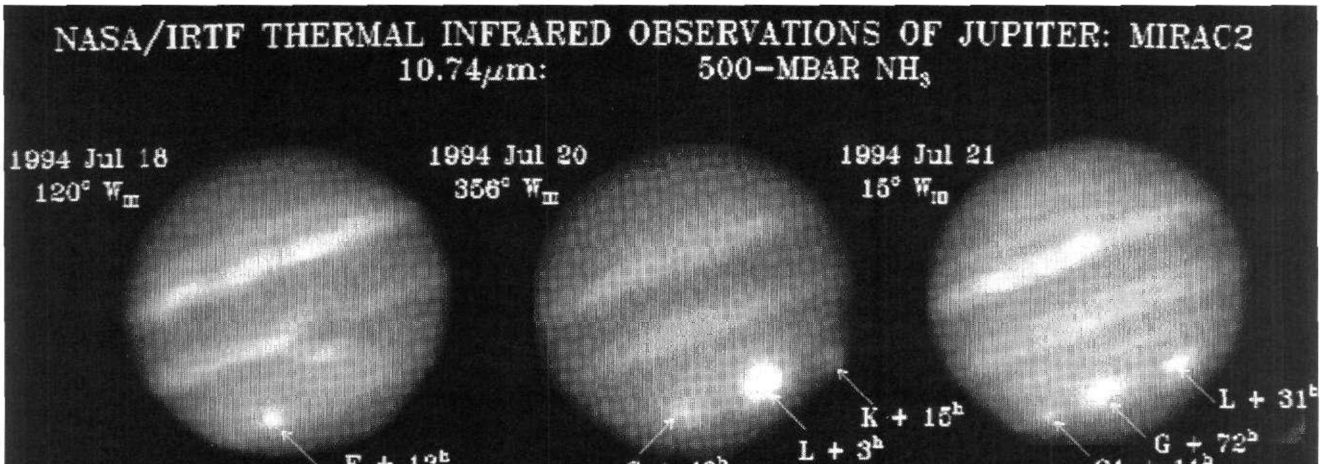

Figure 8. Impact L and other sites at 10.74μm, from the NASA IRTF. At this wavelength the planet is seen by thermal emission modulated by ammonia. Site L on its first passage shines very brightly as it is still warm (second panel; note this image has been darkened to compensate). Older sites, including L the next day (third panel), probably shine by thermal emission from ammonia flung up into the stratosphere. *(Glenn Orton & colleagues, from p. 123 of ref. 5.)*

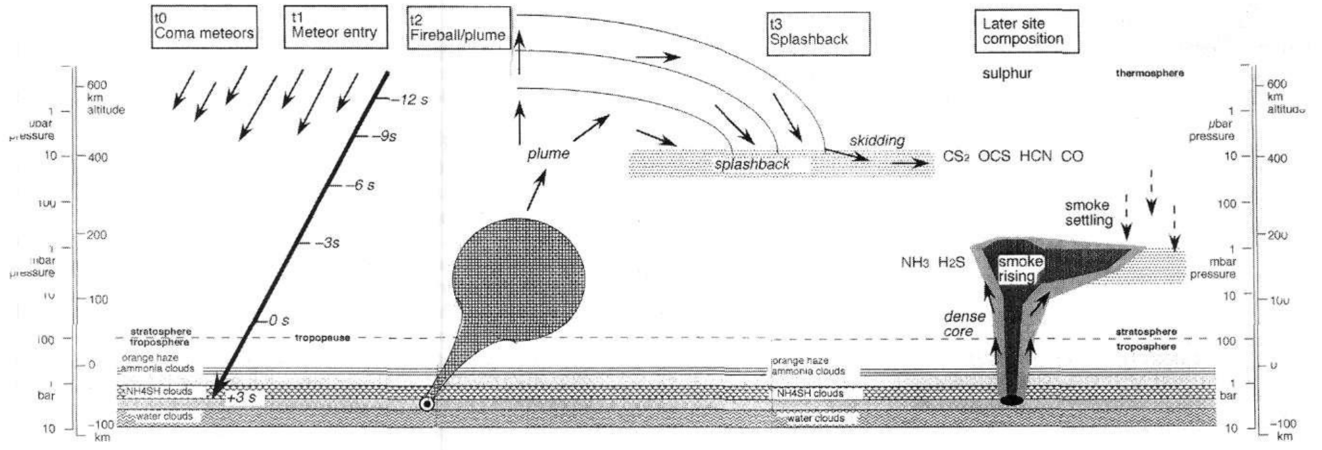

Figure 9. Vertical profiles of the successive stages of a typical impact. Note compression of the vertical scale at the top; there is no horizontal scale.

the splashback, but that the original impacts did reach the cloud-tops.

Chemistry of the impacts

This event could give unique direct information on the composition of both the comet and Jupiter. The aim is to sort out what molecules were present in the comet and in Jupiter's clouds. However, this is difficult because both should contain a similar range of elements (Jupiter's being in hydrogen-rich compounds), and the temperature in the fireball should dissociate and ionise all the molecules of the comet and some of Jupiter's. What comes out will be a chemical equilibrium of H, C, N, O and any other elements from both sources, cooled rapidly from thousands of degrees, plus a cooler plume of intact jovian 'air' brought up around the explosion. There is still a lot of work to be done in analysing the spectra. Table 5 lists molecules detected and estimates of their abundance.

In Jupiter's atmosphere, the main gases other than hydrogen and helium are CH_4 (at all levels), NH_3 (in and below the ammonia clouds), and hypothetically H_2S (in and below NH_4SH clouds) and H_2O (in and below water clouds). Confirmation of jovian H_2S and H_2O would be a major advance. On the other hand, all the amounts in Table 5 could have been contributed by elements in the comet. (A 1km^3 cube is 10^{15}g at the density of ice.) Also, based on impact models, all these molecules are reasonable products of a comet exploding in Jupiter's atmosphere. By heating the impactor and atmosphere to thousands of degrees first at impact, then again in the splash, the model by Zahnle and Mac Low reproduces the observed molecules such as H_2O, CO, S_2, CH_4, HCN, and C_2H_6 (ethane) in abundance. The most critical requirement is to avoid producing lots of SO_2, which was not observed; this suggests that oxygen and sulphur were physically separate, probably from cometary water and jovian clouds respectively.

The idea that cometary and jovian materials remained partially separate was developed at the STScI meeting, where observers and modellers found themselves agreeing that the two sources may be distinguishable. All modellers agreed that the greatest proportion of cometary material is ejected in the fastest part of the plume, which rises higher, comes down later and hotter, and forms the outer part of the visible dark cloud. And observers reported that emission from water and carbon monoxide (EIR from AAT) and from metal atoms (optical from La Palma) did not begin until 10–12 min after impact, halfway through the main event or splashback, consistent with these being mainly cometary materials. Conversely the sulphur (UV from HST) was detected in spectra of the central dark clouds, and may have come from Jupiter's clouds (though it was very high up). There was also evidence for vertical layering in the impact sites later on (Figure 9): new molecules like CO, OCS, CS_2, S_2, and HCN were observed in the upper stratosphere (above the 0.1 millibar level), where they were formed in the splashdown, whereas NH_3, H_2S (?), and much of the dark smoke, were mainly in the lower stratosphere (around 1–10 millibar), brought up from the explosion site and/or Jupiter's clouds by thermal convection later. This suggests a working hypothesis along the following lines:

Table 4. Observed heating above the impact sites

Level	*Temperature increase (site, age)*	*Molecule observed*	*Observatory*
Stratosphere:			
2 µbar	+100° (L, t+4 hr)	CO	CFHT
1-10 µbar	+37° (L, t+11 hr) [still +16° in K, t+23 hr]*	CH_4	IRTF
0.1-1 mbar	+30° (G+Q+R+S, July 21)*	CO	IRAM (& CFHT)
1-10 mbar	+4°? (L, t+12 hr, etc.)	CH_4	Palomar
10-30 mbar	+4° (Q+R, t+10 hr) [still +2° in L&E, t+1 d]*	CH_4	IRTF
Troposphere (cloud-top level):			
200-400 mbar	+2° (L, t+3 hr; G, t+12 hr) [still +1° in K, July 28]	H_2	IRTF

Data mainly from review by Barney Conrath, and ref.8. See Fig. 7 for altitude scale.
* At all stratospheric levels the heating disappeared within a week – much more quickly than expected. Indeed, according to E. Lellouch, the IRAM millimetric spectra showed the G-Q complex was 8-15° cooler than normal by July 28 as the CO lines had changed from emission to absorption. The stratosphere was perhaps refrigerated by radiation from the impact molecules.

Table 5. Molecules observed

(estimated total mass per large impact in grams)

(A) Emission in main event	
CH_4	5×10^{13}
H_2O	2×10^{12}
CO	2×10^{12}
metals	4×10^{10}
(B) Emission in warm stratosphere at fresh impact site	
CO	2×10^{14}
NH_3	$1\text{-}2 \times 10^{13}$
OCS	3×10^{12}
CS	5×10^{11}
	or 10^{10} to 10^{13}
HCN	6×10^{11}
Si	10^{8} to 10^{13}
Fe & Fe^{+}	5×10^{8}
Mg & Mg^{+}	5×10^{7}
(C) Absorption in stratosphere later	
NH_3	$1\text{–}4 \times 10^{11}$
H_2S	$1\text{–}2 \times 10^{12}$
S_2	$\geq 1 \times 10^{12}$
CS_2	1×10^{11}
smoke	10^{13} to 10^{14}

Notes to Table 5

This table includes both EIR and HST UV results. Some of these are still very preliminary values, presented at the DPS and STScI meetings, not intended to be accurate to better than a factor of 10. Some are lower limits because not all the molecules would have been at the correct temperature or altitude to be observed. HST measurements in the 0.86" diameter aperture have been arbitrarily multiplied by 10 to estimate the whole site. Some of the values are from a review talk by E. Lellouch; others are from presentations by K. Noll (HST), R. Yelle, C. A. Griffith (IRTF), R. Knacke (UKIRT), E. Lellouch (IRAM), A. Fitzsimmons (JNT). Any errors or misinterpretations may be due to the present author.

Notes on individual molecules

CH_4 (methane): Hot methane (~1000°K) produced intense emission bands in the main event, which faded rapidly and disappeared within 30 minutes as the plume cooled. This may be methane from Jupiter's stratosphere or from the fireball.

H_2O (water): Water vapour was only belatedly recognised in the spectra, but was actually abundant in the plume or splashback. The Kuiper Airborne Observatory recorded water in several wavebands, including three emission lines near 7.7μm (in 'main event' of G and K; at ~1000°K), in among numerous hot-methane emission lines, all of which faded over minutes and disappeared within 1 hour. The AAT recorded similar behaviour of water emission at 2.0 and 2.4μm in the second half of the main event (D. Crisp & V. Meadows). This behaviour implies that the water came from the comet. There was no 'cool water' such as might have been brought up from Jupiter's clouds. In the smaller impacts R and W, both the KAO and AAT teams saw much less water emission.

CO (carbon monoxide): Hot CO lines were also very prominent in many EIR main event spectra, in the second half of the splashback at ~2000–3000°K. For example, the UKIRT team reported for impact R extremely strong CO emission which lasted no more than ten minutes, as it turned to absorption – attributed to CO in the outer part of the blast which was cooling – and then disappeared. In fact it was cooling so fast that the mass may be greatly underestimated. CO may have been formed from cometary water, the oxygen being combined with carbon from the comet or from the jovian methane.

CO persisted in the impact sites for weeks thereafter. Observers at the IRAM radio telescope reported CO (and CS) emission lines in sites one day old, at the 10–100 μbar level. Later IRAM observations showed CO and CS in absorption well into 1994 August, but surprisingly, CO disappeared by November.

NH_3 (ammonia): According to several observers at the IRTF, enhanced emission from the upper atmosphere at 10–11μm was probably due to enhanced NH_3 content (Figure 8). A large amount appeared in the stratosphere over a few hours (mainly in the 1–10 mbar range) and declined over days as the stratosphere cooled. This must have come from Jupiter's atmosphere, in or below the ammonia clouds.

HST observed NH_3 as UV absorption lines and it remained present up to 1995 April.

H_2S (hydrogen sulphide): Not certain because seen only as a single broad UV band, but the HST UV team were fairly confident. Disappeared in August.

S_2 (sulphur): From HST UV spectra in the core of site G. An earlier mass estimate has been greatly reduced with further analysis: R. Yelle reports that it was at high temperature and must therefore be above the stratosphere. But there might be more, unseen, deeper down. Disappeared in August.

CS, CS_2 (carbon sulphides): Expected shock products. Remained abundant through August, but CS_2 gone by 1995 April.

HCN (hydrogen cyanide): Probably from shock chemistry (very like CO and CS). HCN and CS were still strong in absorption in 1994 November (IRAM).

Si (silicon): Must be from the comet, presumably originating as metal silicates. SiO was not seen in HST UV absorption spectra (< 6×10^{11}g), but may account for a broad emission band in IRTF emission spectra (~10^{13}g).

Na, Fe, Mg, etc. (metals): Must be from the comet, but not much is needed to give the emissions observed. In the main event, metal emission was observed by the INT (A. Fitzsimmons): it began with Na lines at t1+10 min, and other metal lines appeared 6 min later (600–1000°K). The amount is worked out from the Na lines assuming cosmic ratios of other metal compounds. But the later lines were not in cosmic ratios, possibly because the emissions were produced only by metals which had already recondensed into solid grains and were then vapourised again in the splashback.

Other metals and hydrocarbons were also detected.

SO_2 (sulphur dioxide) was not detected by IRAM (<3×10^{12}g) nor HST (<10^{11}g in aperture).

N_2 (nitrogen) is not observable but may be abundant, to make up the cosmic proportion of nitrogen.

(i) Outer, hotter, later part of splash: 1–100 μbar level: formed from fireball, much cometary material rich in C & O & minerals, reacting again with jovian stratosphere: produces CO, H_20, metals, SiO?, brown gunk. Poor in S, or SO_2 would have been seen.

(ii) Inner, cooler part of splash: 1–100 μbar level: from fireball, mainly jovian material rich in H & C & N & S; contains S_2, CS, CS_2, OCS, HCN.

(iii) Core, rising from site of explosion: 1–100 mbar level: from fireball plus surrounding jovian 'air', rich in H & C & N & S; brings up molecules of (ii) with NH_3, H_2S, and brown gunk.

Such a model remains to be worked out properly, and this outline is no doubt inaccurate. For a start, each zone included a wide range of temperatures. In (i), the observed temperatures were ~2500°K for CO but only ~600–1000°K for water and metals and dust; in (ii), at least 2000°K is needed to produce these molecules. Anyway, astronomers will now be interpreting spectra in the knowledge that the radial and vertical layering of these molecules may enable their origin to be sorted out.

What is the visible dark 'smoke' (Figure 2)? According to analysis of HST images by Robert West and colleagues,[6] it is actually slightly brownish though the spectrum shows no distinct features. Soot (carbon) is not favoured, neither theoretically nor observationally. The best alternatives are dirty silicates from cometary minerals ('dust') or hydrocarbon polymers ('gunk'). Various forms of gunk can mimic the spectrum, including organic material from a carbonaceous chondrite, or poly-HCN, or other organics rich in S and N. Gunk is also favoured because it could well form in the impacts, and it could condense near 160°K to make visible the transient expanding wave. It could also form a coating on smaller silicate grains.

West calculated that the total volume of dark debris amounts to a sphere ~1.0km across (~10^{15}g). From various visible and IR images, Kevin Baines (IRTF), and D. Wellnitz et al. (Perth), and F. Moreno et al. (WHT)[7] all estimated ~10^{13}g of dust in a single large impact site.

Both Baines et al. (IRTF data) and West et al. (HST data)[6] calculated the sizes and altitudes of the reflecting smoke particles in the hours and weeks following the impacts. According to West, in the black cores, the smoke extends from ~1 mbar to >200 mbar (i.e., possibly to the visible cloud-tops around 500 mbar); in the more extended haloes, a range from <1 mbar to ~10 mbar fits the data. Particles were getting larger by coagulating while the total amount visible remained constant (to late August). Baines agreed that the top was around 0.3–1.2 mbar, but by October, the sites had faded at 3.4μm but were still visible at 2.3μm, indicating a settling of debris below the 1 mbar level.

The development of the visible smoke clouds is described in Paper II, which is the Jupiter Section Report on the comet impacts.

Acknowledgments

I acknowledge all the researchers who presented data at the DPS and STScI conferences; space prohibits citing everyone by name. I also thank those people who kindly provided illustrations, and Mike Foulkes, James Lancashire and Simon Mentha for their help in preparing this report.

Address: 10 The Woodlands, Linton, Cambridge CB1 6UF

Note added in proof

The Galileo Probe has apparently detected jovian H_2O and H_2S in near-solar abundances below the clouds, but as many of the Probe results differed from predictions, some aspects of the comet crash models may have to be revised.

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Editor's note: The second and third papers in this series, No. II, 'The visible scars', and No. III, 'The largest impact complex at high resolution' (by Rogers, Miyazaki & Limaye), will appear in the June *Journal*.

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The comet collision with Jupiter: II. The visible scars

John H. Rogers

A report of the Jupiter Section (Director: John H. Rogers)

The comet impacts on Jupiter in 1994 July produced extremely dark spots, some of which were the most conspicuous transient features ever observed on the planet. Here we report the observations of them by BAA members and other amateurs. The size of each visible 'scar' was roughly in proportion to the reported infrared brightness of the fireball. The scars appeared at least as dark when near the limb as when fully on the disk. Most of the scars lasted more than a month, and their average rotation period was very close to that of the SSS Temperate Current or System III, as expected. However, there was evidence for diverse local motions. At first, the black core regions tended to have slower rotation periods (average $\Delta\lambda_2 = -2$ (±5)°/month, omitting multiple impact sites). But the leading edges and peripheral clouds, and whole sites later, moved faster (average $\Delta\lambda_2 = -18$ (±12)°/month); this seems to reveal a stratospheric current faster than the underlying cloud-top current. By mid-September, the sites had merged into an uneven new belt that encircled the planet, and this 'impact belt' persisted into 1995.

Introduction

In 1994 July, 20 fragments of Comet Shoemaker–Levy 9 crashed into Jupiter at speeds of 60 km/s. This unprecedented event was predicted a year in advance so every observatory and spacecraft that could observe it was made ready to do so. The times and longitudes of the impacts are listed in Table 1.

Table 1. Accepted impact times and longitudes.

Fragment	*July (d)*	*Time (hr:min:sec)*	λ_3	λ_2	*Magnitude of scar*
A	16	20:11:50	185.4	114.3	3b
B	17	02:50:—	(67)	(356)	1
C	17	07:10:40	223.1	152.0	3b
D	17	11:53:10	33.7	322.6	2
E	17	15:12:00	153.4	82.3	4
F	18	00:37:—	(137)	(65)	0
G	18	07:33:32	25.8	314.4	5
H	18	19:31:59	100.6	29.2	4
K	19	10:24:13	278.5	206.8	5
L	19	22:16:48	348.6	276.8	5
N	20	10:29:17	72.6	0.6	1
P2	20	15:23:—	(251)	(179)	0
Q2	20	19:44:00	46.0	334.0	1
Q1	20	20:13:52	63.5	351.5	3a
R	21	05:35:03	43.0	330.8	3a
S	21	15:16:00	33.0	320.7	3x
T	21	18:11:—	(141)	(69)	0x
U	21	21:56:—	(277)	(204)	0x
V	22	04:23:10	(150)	(78)	0x
W	22	08:06:14	283.3	210.8	3x

Table 1 was prepared by the author from compilations and calculations by P.W. Chodas and D.K. Yeomans.
Accepted impact times: in UT; see ref. 6 for details.
Longitudes: in Systems III and II, derived from these times on the basis of Chodas and Yeomans' ephemeris (as in ref. 7). Note that these agree well with the initial longitude of the black core recorded by the BAA.
Magnitudes of the visible scars: from refs. 6 and 7. These estimates from HST images[7] agree with the BAA observations.
Class 5: covers >10 000 km, with Nf. core and Sp. crescent.
Class 4: 4000-8000 km, core & crescent. Class 3a: as 4 but less ejecta. Class 3b: as 4 but core fainter and shorter-lived. Classes 2 and 1: <3000 km, HST saw core only (± short streak to Sp.), visual observers saw nothing. Class 0: no scar visible. x , These impacts were close to pre-existing scars which may have masked a weak fireball and scar.

The Jupiter Section report on Jupiter in 1994 before the impacts is in preparation. BAA publications have already given details of the comet itself and predictions for the impacts,[1,2] first reports of the impacts,[3,4] methane-band images of the impact debris,[5] summaries of the later development of the visible impact scars,[5] and a review of professional analysis of the impacts (Paper I of this series).[6] (Other early amateur reports were in references 8–10.) The present paper is the Section Report on the events; refs. 4 and 5 should be regarded as adjuncts to it, and a further note (Paper III) will describe higher-resolution views of the largest impact complex.

This report describes observations by amateurs all around the world, both BAA members and others. As listed in Table 2, there were 98 contributors from 19 countries representing 6 continents. This does not even include all the observers of national societies in Belgium, Finland, France, Italy, and Japan, some of whose work was kindly forwarded to us by the national Jupiter coordinators. Only Antarctica is missing, although e-mail messages from the professional infrared observers at the South Pole gave early news of most of the impacts.

Jupiter was at declination 12°S during the impacts, so southerly observers were favoured. British observers were hindered by the planet's low altitude in the evening twilight, but were helped by remarkably good weather during impact week, so only one of the seven evenings was lost to cloud for most observers. We were also favoured in our longitude, in that we could view the planet just after several of the major impacts. In contrast, very few observations were received from the southern hemisphere.

Some of the most detailed and long-continued observations[5] were from Carlos Hernandez in Florida, and from P. Devadas and his daughter Mrs Komala Murugesh in India, as well as the set of CCD images by Isao Miyazaki on Okinawa.

All the impacts occurred a few degrees round the dark limb, so that impact flashes were not expected to be directly

Table 2. Contributing observers

Observer	*Location*	*Telescope*
G. Adamoli	Verona, Italy	110mm OG
F. Balella	Ravenna, Italy	152mm OG
S. Beaumont	Windermere, Cumbria	300mm refl.
A. Bernasconi	Milan, Italy	250mm refl.
R. Billington	Nether Alderley, Cheshire	215mm refl.
I. Bikker & L. Blommers	Leiden, Netherlands	266mm OG
M. Bosselaers *et al.*	Ukkel, Belgium	405mm Presman–Camichel & 450mm OG (July);
M. Bosselaers	Izana Obs., Tenerife, Spain	115mm Schiefspiegler (Aug.)
A. G. Bowyer	Epsom Downs, Surrey	300mm refl.
D. Bruton	College Stn., Texas, USA	360mm Sch.Cass. (inc. photos)
R. Bullen	Bognor Regis, Sussex	216mm refl.
T. Cave	Long Beach, Calif., USA	various
J. Chapple	Bristol	203mm Sch.Cass.
M. Cicognani	Grisignano, Forli, Italy	102mm OG
E. Colombo	Milano, Italy	254mm refl.
A. C. Cook	Camberley, Surrey	200mm refl. (CCD-video)
M. Cook	Camberley, Surrey	90mm Mak.–Cass.
W. Cuppens	Gruitrode, Belgium	203mm Sch.Cass., etc.
P. Devadas & K. Murugesh	Madras, India	250mm refl.
H. Eggendinger	Freising, Germany	150mm OG
A. Farr	Garforth, W. Yorks.	102mm OG
G. Farroni	St. Avertin, Tours, France	
D. Fernandez B.	Barcelona, Spain	158mm refl. & 203mm Sch.Cass.
M. Foulkes	Hatfield, Herts.	203mm Sch.Cass. & 254mm refl.
A. Fuggle	Folkestone, Kent	203mm Sch.Cass.
J. Gargett & A. Kennedy	Ferryhill, Co. Durham	254mm refl.
D. L. Graham	Brompton-on-Swale, N. Yorks.	150mm OG
D. Gray	Kirk Merrington, Durham	415mm Dall–Kirkham
H. Gross	Hagen, Germany	250mm Schiefspiegler (July, Aug.);
	Puimichel, France	1040mm refl. (Sep.)
D. Hatch	Huntingdon	152mm OG (video)
J. F. Harper	Wellington, New Zealand	200mm Sch.Cass.
T. Haymes	Reading	300mm refl.
A. W. Heath	Long Eaton, Notts.	300mm refl.
M. Hendrie	Colchester, Essex	150mm OG
C. E. Hernandez	Miami, Florida, USA	410mm refl. (July); 200mm refl. (Aug.,Sep.)
N. James	Chelmsford, Essex	300mm refl.
R. Johnson	Ewell, Surrey	80mm OG
P. D. King	Cambridge	310mm OG
R. Konnai	Ishikawa, Japan	356mm Sch.Cass.
J. Lancashire	Cambridge	200mm & 310mm OG
A. A. Langley	Aberdare, Mid-Glam.	220mm refl. (video)
D. Lloyd	Worcester	150mm refl.
N. Longshaw	Oldham, Lancs.	200mm Sch.Cass.
L. T. Macdonald	Newbury, Berks.	222mm refl.
J. Mackey	Peterborough	280mm Sch.Cass.
R. J. McKim	Calif. & Arizona, USA; Oundle, Northants.	various (July); 216mm refl. (Aug.)
H-J. Mettig	Dresden, Germany	150mm coudé OG
H. Miles	Wadebridge, Cornwall	130mm OG
I. Miyazaki	Okinawa, Japan	400mm refl. (CCD)
M. P. Mobberley	Chelmsford, Essex	490mm refl. (CCD)
P. A. Moore	Herstmonceux, Sussex	660mm & 330mm OG
S. Moore	Fleet, Hants.	356mm refl.
A. Nikolai	Berlin, Germany	150mm OG
D. C. Parker	Florida, USA	410mm refl. (CCD)
T. Platt	Binfield, Berks.	320mm refl. (CCD)
J. Pougel	Luanda, Angola	280mm Sch.Cass. (photos)
G. C. Rigato	Caltana, Venezia, Italy	124mm OG
J. H. Rogers	Cambridge	310mm OG
R. Royer	Lakewood, Calif., USA	320mm refl. (CCD-video)
A. Sanchez Caso	Barcelona, Spain	254mm refl.
R. W. Schmude	College Stn., Texas, USA	360-mm Sch.–Cass. (inc. photos)
J. D. Shanklin	Cambridge	150mm & 200mm OG
A. Snook	Dover, Kent	310mm refl.
D. P. Stephens	Solihull	220mm refl.
D. Storey	Witney, Oxon.	80mm OG
D. Strange	Worth Matravers, Dorset	300mm refl. (CCD)
J. Stuckey	Beaver Meadow Obs., New York, USA	320mm (CCD) (via Internet)
T. Tanti	Malta	203mm Sch.Cass.
C. Taylor	Hanwell Castle, Oxon.	320mm refl.
M. Taylor	Wakefield, W. Yorks.	100mm OG, etc.
T. Teague	Chester	63mm OG
G. Teichert	Hattstatt, France	280mm Schmidt–Cass.
L. Testa	Parma, Italy	150mm OG (CCD)
D. F. Trombino, B. Pepin, et al.	Florida, USA	150mm OG
D. M. Troiani	Illinois, USA	200mm refl.
A. G. Vargas B.	Cochabamba, Bolivia	200mm refl.
F. Ventura	Malta	100mm OG
E. Verwichte	Genk, Belgium	200mm refl.
J. Warell	Uppsala, Sweden	160mm OG
S. C. Williams	Grove Creek Obs., Trunkey, NSW, Australia	360mm Sch.Cass. (CCD) (via internet)
J. Youdale	Billingham, Cleveland	150mm Mak.–Cass.

A few notes or observations were also received from: M. Boschat (Canada), T. Broadbank, M. Cullen (Botswana), P. Doherty, D. Herbert, J. Knott, M. Solano–Ruiz (Tenerife), A. Vincent, J. G. Williams, J. Wootton (New Zealand).

The following representatives kindly sent data from their national societies:

G–L. Adamoli	Unione Astrofili Italiani
M. Bosselaers	Vereniging voor Sterrenkunde (Belgium)
C. Hernandez	Association of Lunar & Planetary Observers (USA)
M. Jacquesson	Société Astronomique de France
T. Nyberg	Ursa Planet Section (Finland)

We also thank Seiji Kimura for the published proceedings of the JAAC meeting;[10] this volume contains many fine drawings, maps and images, which confirm the conclusions in the present report.

Near-infrared images in the 0.89μm methane band were taken by Isao Miyazaki,[5] and a few also by Don Parker. Latitudes (zenographic) were measured from Miyazaki's images, typically ±1°.

visible, but the impact sites rotated into view within less than an hour. Twelve fragments produced bright infrared plumes and very dark visible impact scars. For the first eight of these (A, C, D, E, G, H, K, L) these effects were roughly in proportion to the brightness of the fragment before impact. For the later four (Q1, R, S, W), the bright infrared plumes were shorter-lived and the dark visible scars were smaller; in fact the scars of impacts S and W were not resolved visually as they were superimposed on sites K and (D+G) respectively. Thus a total of nine visible scars resulted. Another eight fragments, which were either very small or displaced off the main line (B, F, N, P2, Q2, T, U, V), produced little or no effect on impact, while another four fragments had already drifted off-line and disappeared before impact.

These differences between fragments may have been due to uneven density or composition of the original comet.

The best visible-light images were of course from the Hubble Space Telescope (HST).[7,8] They included the actual plumes of impacts A, E, G, and W; these sites as well as Q1 and R on their first passage, revealing details of the 'scar' and a narrow expanding wave; several images of sites evolving during the impact week; and global maps on July 23, July 30, and August 24.[5] While these superb images confirm and extend much of what we saw, we also observed at times when HST could not, both during and after impact week, so the results reported here are much more complete in time coverage.

The predicted zenographic latitudes for the 12 major on-line fragments ranged from 47.0°S (impact A) to 48.1°S (impact W), increasing steadily at 0.1° per fragment.[2] The actual impact latitudes measured from HST images were, on average, within 0.15° of these predictions.[7] (The off-line fragments were predicted to impact 0.0–0.8° further south.)

The impacts were thus in the SSS Temperate domain, which extends from 53.4°S to 43.6°S (Figure 1C).[11,12] It is divided by a modest retrograding jetstream at 49.4°S. Visible spots are rare in this domain, and when they appear, they move with the SSS Temperate Current, whose mean motion of $\Delta\lambda_2$ = –8.3 deg/mth is virtually identical to System III ($\Delta\lambda_2$ = –8.0 deg/mth), the rotation period of the planet's deep interior. As usual, there were no prominent features in this latitude before the impacts. However, there were conspicuous structures in the SS Temperate domain (36–43°S, moving with the SSTC at $\Delta\lambda_2$ ~ –25 deg/mth) (Figure 1A, B). These included five dark patches of true SSTB at about 40°S, associated with five tiny white ovals at 41°S, as well as some larger bright areas. With the possible exception of one white spot which brightened (see site G, Paper III), these features were unaffected by the impacts. They need to be noted, however, as they could sometimes be confused with the outer parts of the impact sites.

The impact week

The visible scars were extremely dark clouds, clearly unique in the history of Jupiter observation. They were the darkest features on the planet. Their size was roughly in proportion to the reported magnitude of the infrared plume; some of them grew larger than the Great Red Spot.

Figures 2–7 show the astonishing changes in appearance of Jupiter's southern hemisphere as impact week progressed, as seen from five longitudes spaced around the world. (Also see the impact week sequence and images from other British and Swedish observers in ref.4.)

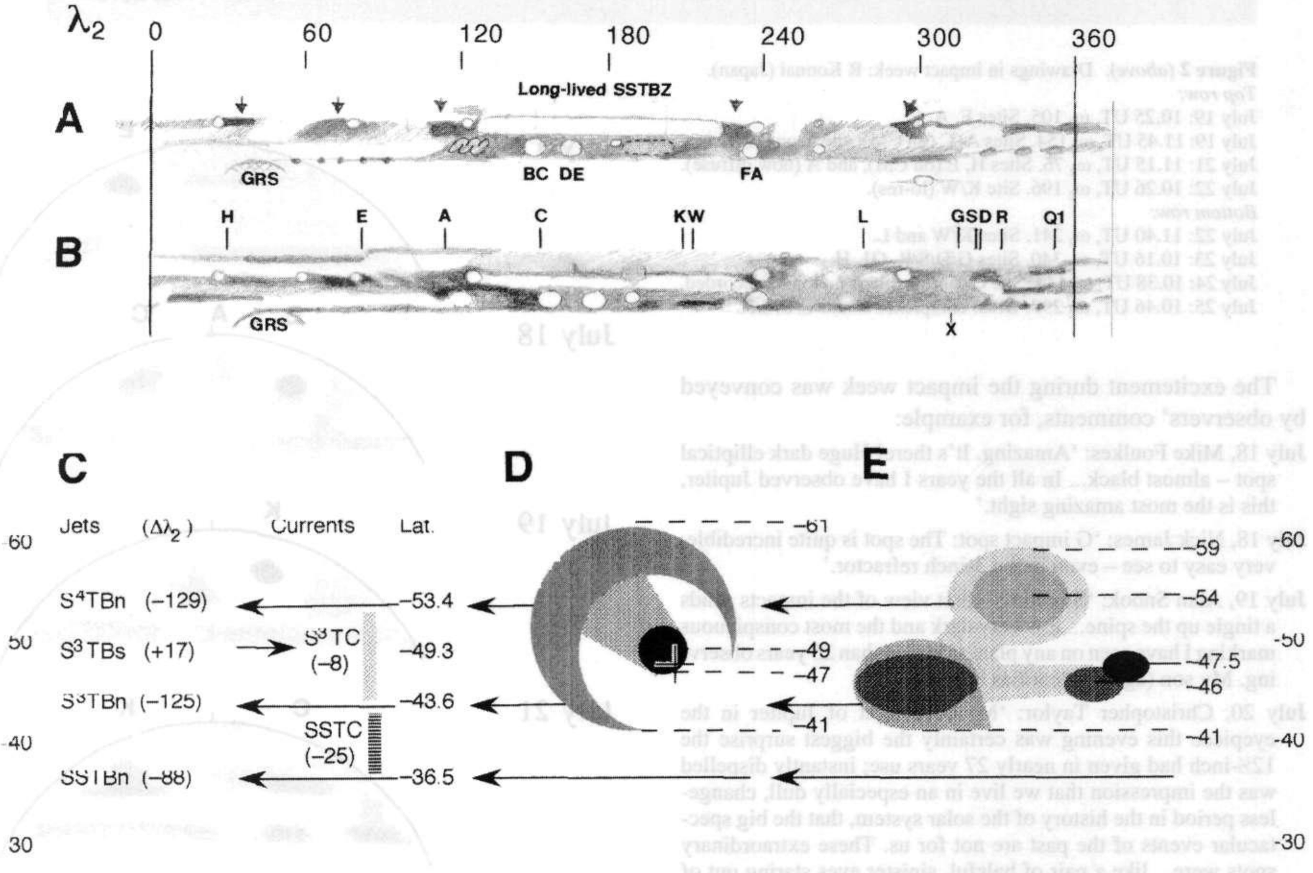

Figure 1. Locations of the impacts. The impacts were at 47–48°S, in the SSS Temperate domain, which had no major features beforehand.
(A, B). These strip-maps show the pre-existing visible cloud features just north of the impact region, in the SS and S. Temperate domains. They include five dark patches of true SSTB (~40°S; arrowed in A), associated with five anticyclonic ovals at 41°S, moving with the SS Temperate Current ($\Delta\lambda_2$ ~ –25°/mth); and the revived STB with ovals BC, DE, and FA ($\Delta\lambda_2$ ~ –13°/mth). The 'long-lived SSTBZ' is a well-defined sector of cyclonic (nominal SSTB) latitude that has been bright since 1992. (A) Forecast from Miyazaki's images in May, with features rolled forwards to impact week with the above drift rates. (B) Actual arrangement in impact week according to Miyazaki's images on July 13–17. X marks the cyclonic white oval at 38°S that brightened after impact G (Paper III). Longitudes of the impacts from Table 1.
(C). Normal currents in the region: speeds ($\Delta\lambda_2$, degrees per 30 days) and latitudes (zenographic) in the SSS and SS Temperate domains. Jetstreams (left) define the boundaries of the domains; slow currents (S^3TC and SSTC) govern spots within the domains.
(D, E). Sketch-maps of the dark scar of impact K, with zenographic latitudes measured from Miyazaki's images, typically ±1°. (D) July 19, on first passage; cross marks the impact point from ephemeris and HST data. Sites L and G were essentially the same (Paper III). (E) July 24–27.

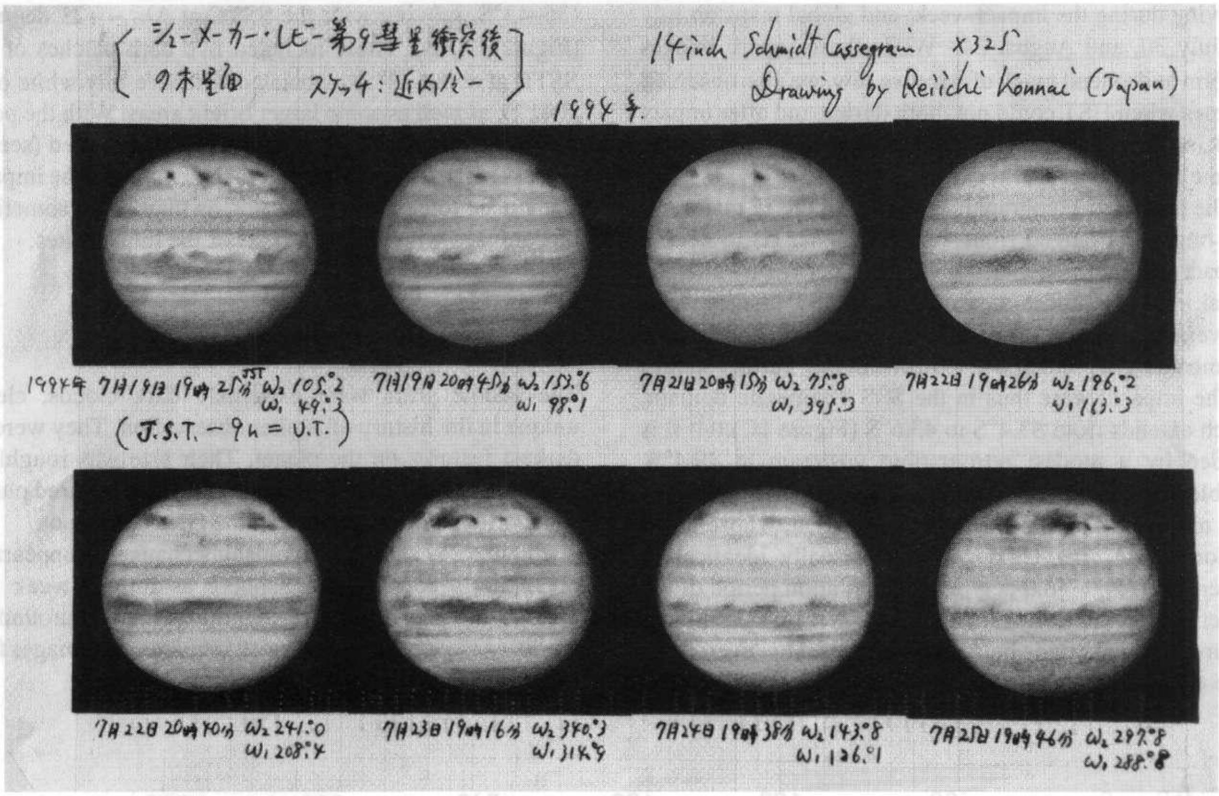

Figure 2 *(above).* Drawings in impact week: R Konnai (Japan).
Top row:
July 19: 10.25 UT, ω_2 105. Sites E, A, C.
July 19: 11.45 UT, ω_2 154. Sites A; C (on CM); and K on first rising.
July 21: 11.15 UT, ω_2 76. Sites H, E (on CM), and A (now diffuse).
July 22: 10.26 UT, ω_2 196. Site K/W (lo-res).
Bottom row:
July 22: 11.40 UT, ω_2 241. Sites K/W and L.
July 23: 10.16 UT, ω_2 340. Sites G/D/S/R, Q1, H.
July 24: 10.38 UT, ω_2 144. Site C central; site A no longer recorded.
July 25: 10.46 UT, ω_2 298. Great complexes L and G/D/S/R.

The excitement during the impact week was conveyed by observers' comments, for example:

July 18, Mike Foulkes: 'Amazing. It's there! Huge dark elliptical spot – almost black... In all the years I have observed Jupiter, this is the most amazing sight.'

July 18, Nick James: 'G impact spot: The spot is quite incredible, very easy to see – even in the 3-inch refractor.'

July 19, Alan Snook: 'Stunning – first view of the impacts sends a tingle up the spine... E is very dark and the most conspicuous marking I have seen on any planet in more than 25 years observing. My son (age 5) identifies it easily.'

July 20, Christopher Taylor: 'My first sight of Jupiter in the eyepiece this evening was certainly the biggest surprise the 12½-inch had given in nearly 27 years use; instantly dispelled was the impression that we live in an especially dull, changeless period in the history of the solar system, that the big spectacular events of the past are not for us. These extraordinary spots were... like a pair of baleful, sinister eyes staring out of the face of Jupiter.'

July 20, Patrick Moore: 'The best view so far. The impact sites are amazingly dark and vast. Checked all this with a CCD on the 26-inch – and made a broadcast to Europe from the dome – TV crews also there. Definition failed after 22.00 as Jupiter descended. By then the result of fragment Q was emerging.'

(These comments from Herstmonceux closely parallel what we were experiencing at the same time at Cambridge, with the

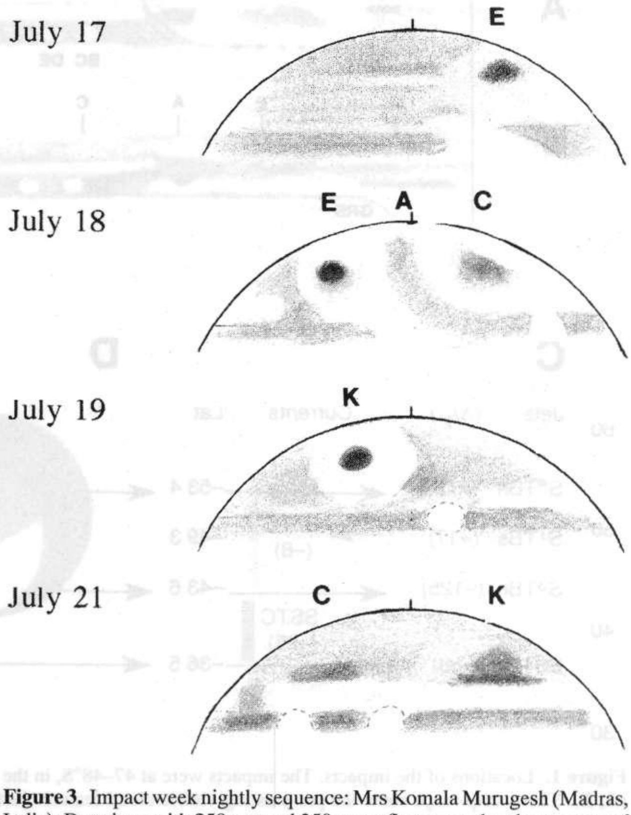

Figure 3. Impact week nightly sequence: Mrs Komala Murugesh (Madras, India). Drawings with 250mm and 350mm reflectors at the observatory of P. Devadas.
July 17: 17.00 UT, ω_2 44, seeing II. First view of impact: site E on its first appearance.
July 18: 14.45 UT, ω_2 113, seeing II. Sites E, A, C. The 'ring' around C is an illusion due to site A with SSTB and STB; oval BC is on f. side.
July 19: 13.30 UT, ω_2 217.5, seeing III. Site K on its first passage (and oval FA).
July 21: 13.35 UT, ω_2 160, seeing III. Sites C (now a streak) and K.

BBC World Service recording comments by observers and public in the dome of the 12-inch refractor, while across the road many other people watched the giant impact sites on a live video projection at a party held by the Cambridge Astronomical Association.)

After impact week, Johan Warell: 'I have shown [the spots to] lots of friends of mine who have never watched Jupiter before, and they are equally thrilled at the immense structures formed by such small impacting objects.'

The impacts themselves were not seen; at least, the BAA did not receive any definite or confirmed reports of visual flashes, although British and European members were gazing at the planet's limb or at nearby satellites during impacts H, L, Q2 and Q1, and Californian observers during impact R.

However, the dark scars were typically seen about an hour after impact. Sightings of the first site (A) from Britain on its first rising were uncertain due to poor seeing,[3] but later impact sites seen on their first rising included site E (from Madras; Figure 3), H (from many sites in Britain and from the Netherlands; Figure 5), K (from Japan; ref. 5 and Figure 2), and Q1 (from several sites in Britain – Figures 5 & 9 and ref.4). These sites were first perceived as a black 'bite' in the shaded limb, and then as a dark patch rotating onto the disk. Sites H and Q1 on first rising appeared to be fainter

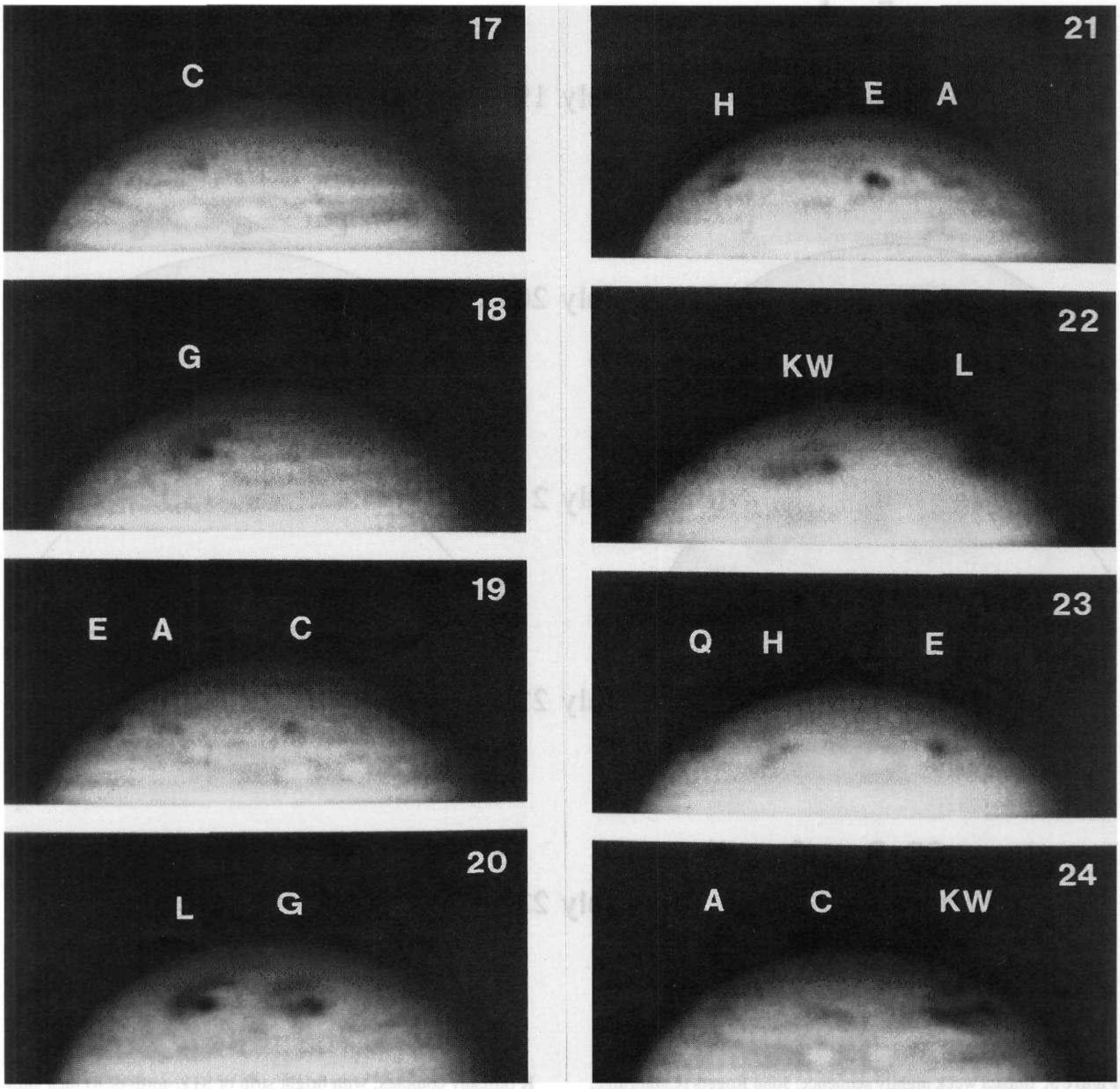

Figure 4. Impact week nightly sequence: Isao Miyazaki (Okinawa, Japan). CCD images on each evening of impact week, taken with a 400mm reflector. July 17: 10.41 UT, ω_2 175. Site C on first passage.
July 18: 10.59 UT, ω_2 336. Site G on first passage; site D is the tiny spot a few degrees f. its black core.
July 19: 11.27 UT, ω_2 143. Sites E, A, C. Site A is now a streak, but site C has a more distinct black core than on July 17.
July 20: 11.49 UT, ω_2 301. Sites L and G. Note that the ejecta crescents are darker than on July 18, and one of the two white spots just Np. site G has brightened (see Paper III).
July 21: 11.16 UT, ω_2 77. Sites H, E, A, with adjacent SSTB segments.
July 22: 11.02 UT, ω_2 219. Site K/W, on first passage since impact W; it is not resolvable from the black core of site K. Site L is on f. limb.
July 23: 12.13 UT, ω_2 51. Sites Q1 (near p. limb), H (split into Sp. cloud and north-streaming dark core), and E (black spot).
July 24: 11.02 UT, ω_2 159. Sites A (near p. limb), C (now a broad streak), and K/W (3 dark spots, on f. side).

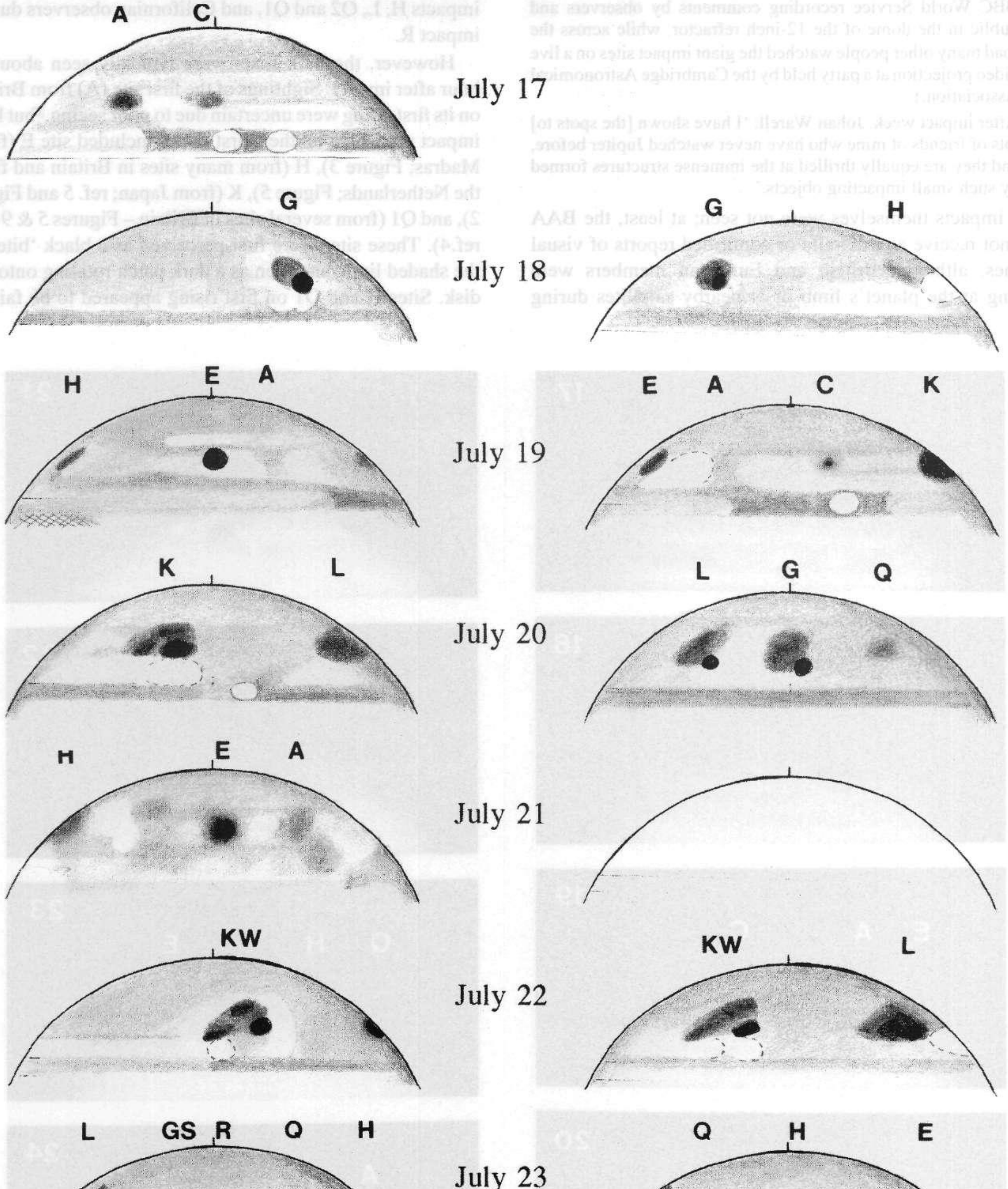

Figure 5. Impact week nightly sequence: John Rogers (Cambridge, England) and others. Drawings by Rogers using the 310mm refractor at the Institute of Astronomy, Cambridge, except for July 21 and 22. S = seeing on Antoniadi scale. (For a nightly sequence by other BAA observers in England, see ref. 4).
July 17: 19.52 UT, ω_2 148, S III. First view of impact sites A and C (with ovals BC and DE).
July 18, 19.26 UT, ω_2 282, S III; 21.10 UT ω_2 345, S IV. Site G, followed by site H on its first appearance with adjacent limb-brightening.
July 19, 19.49 UT, ω_2 86, S III; 21.14UT, ω_2 138, S IV. Sites H, E, A, C, K in succession; site A is fainter than it was two days earlier.
July 20, 19.30 UT, ω_2 225, S III (dim); 21.44 UT, ω_2 306, S V. Site K (already complex, with bright strip of STZ north of it) then sites L and G, then site Q1 faint on its first appearance.
July 21, 21.19 UT, ω_2 81 (drawn by JR from CCD image by D. Strange). Sites E and A, similar to July 19.
July 22, 20.13 UT, ω_2 191, S III; 21.20 UT, ω_2 232, S III–IV. (250mm reflector). Sites K/W (more complex after the final impact in it; STZ still bright north of it) and L (with limb-brightening Nf. it).
July 23, 19.44 UT, ω_2 324, S II–III; 21.25 UT, ω_2 25, S IV–V. Sites L, D/G/S (complex, with bright spot north of it that has erupted from a pre-existing light spot in STZ), R (tiny black spot), Q1, H (its ejecta now a separate cloud, Sp. the core which is displaced to the north), and E (still compact).

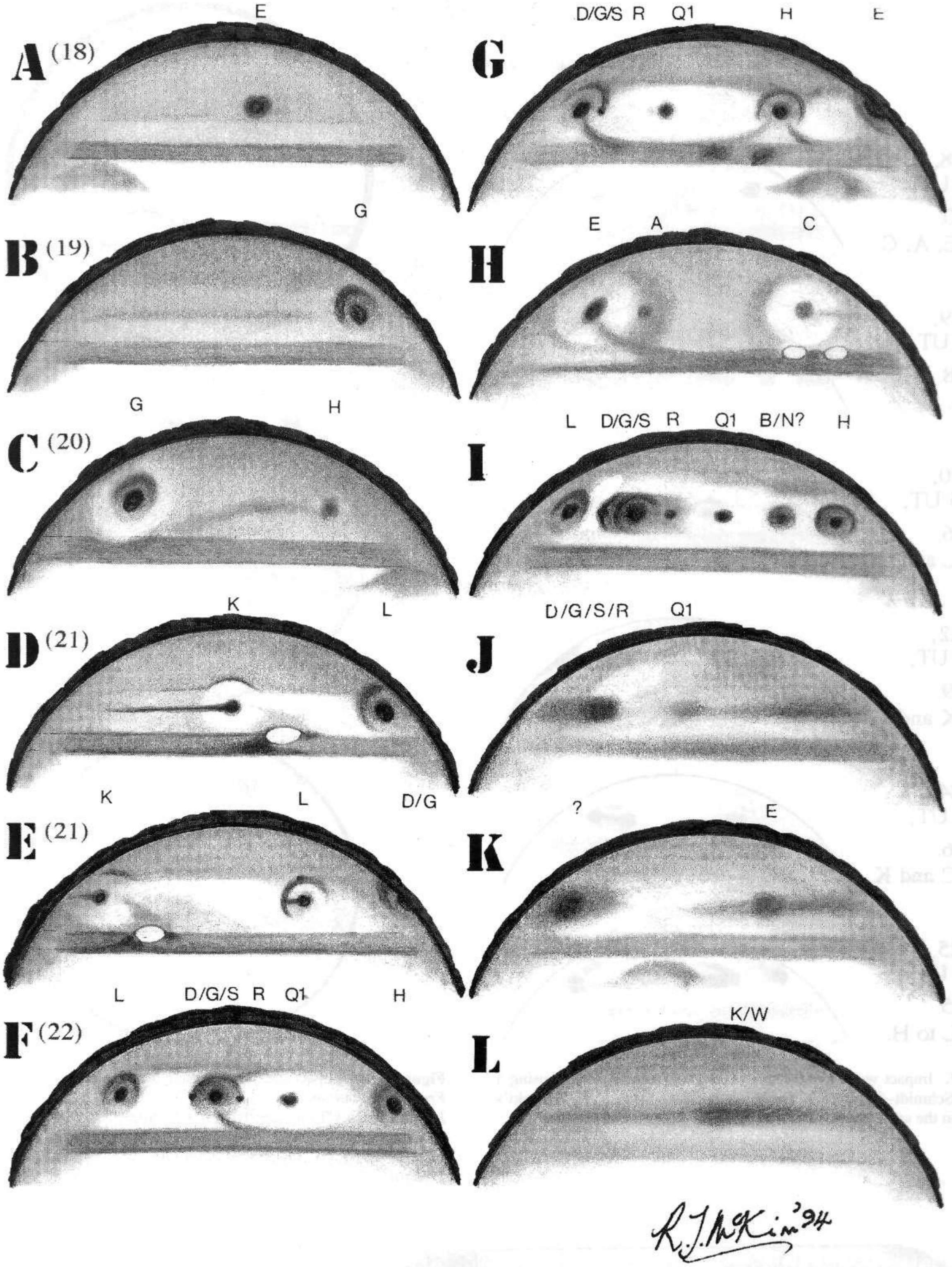

Figure 6. Impact week nightly sequence: Richard McKim (California), and later views.
(A) July 18: 03.30 UT, ω_2 65; 152mm OG, San Gabriel, Calif. Site E.
(B) July 19: 05.07 UT, ω_2 274; 254mm refl. (and CCD on 320mm refl.). Lakewood, Calif. Site G.
(C) July 20: 03.07 UT, ω_2 351; 322mm refl. and 140mm OG, Long Beach, Calif. Sites G and H.
(D) July 21: 05.06 UT, ω_2 213: 457mm refl., Ford Obs. Table Mountain, Calif. Sites K and L.
(E) July 21: 05.55 UT, ω_2 243: as in (D).
(F) July 22: 04.05 UT, ω_2 326: 254mm refl. (and CCD on 320mm refl.), Lakewood Calif. The great array of sites at the end of impact week. Apparent festoons running between impact sites were mostly SSTB features.
(G) July 22: 05.22 UT, ω_2 13; as in (F).
(H) July 23: 04.15 UT, ω_2 123; 152mm OG, Long Beach, Calif. Sites E, A (now diffuse), and C.
(I) July 27, 03.27 UT, ω_2 334; 600mm OG, Lowell Obs., Flagstaff, Ariz. The great array of sites at the end of impact week. ('B/N?' is actually the detached Sp. cloud of site H).
(J) August 16: 20.17 UT, ω_2 346: 216mm refl., Oundle, Northants., England. Complex G/D/S/R on p. side, and impact belt developing on f. side.
(K) August 19: 19.30 UT, ω_2 48; as in (J).
(L) August 27: 19.25 UT, ω_2 116; as in (J).

July 18,
04.45 UT,
ω_2 110.
Sites E, A, C.

July 19,
02.45 UT,
ω_2 188.
Site C.

July 20,
01.35 UT,
ω_2 296.
Sites L and G.

July 22,
01.30 UT,
ω_2 229.
Sites K and L.

July 24,
01.35 UT,
ω_2 176.
Sites C and K.

July 25,
01.50 UT,
ω_2 335.
Sites L to H.

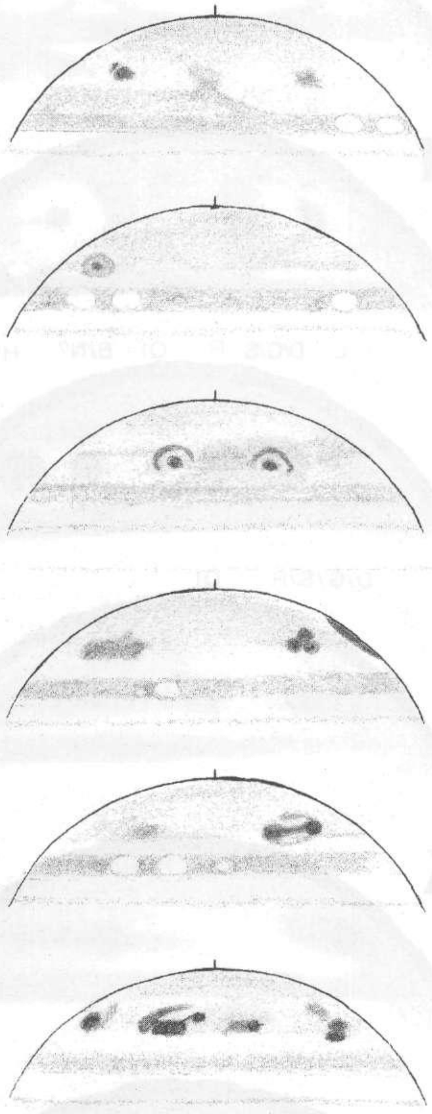

Figure 7. Impact week nightly sequence: Dan Bruton (Texas), using a 360mm Schmidt–Cassegrain. These are one rotation before Miyazaki's images on the same dates.

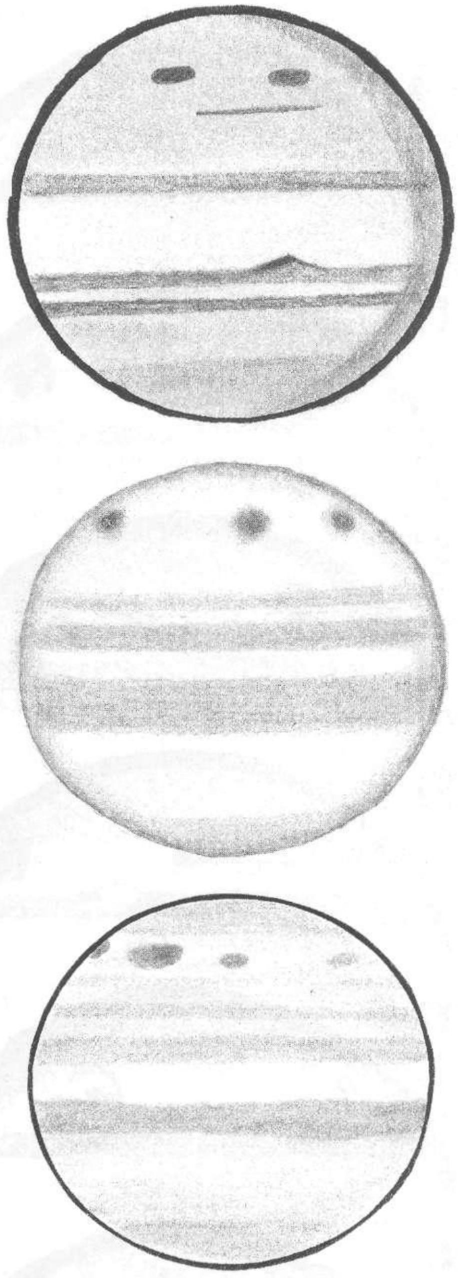

Figure 8. The impact sites were striking features even in small telescopes. *From top to bottom:*
July 22: 21.14 UT, ω_2 228; 102mm OG. Sites L and G. *A. Farr*
July 22: 22.08 UT, ω_2 261; 63mm OG. Sites K, L and G. *E. T. H. Teague*
July 28: 18.55 UT, ω_2 325; 100mm OG. Sites G/D/S/R, Q1 and H. *F. Ventura*

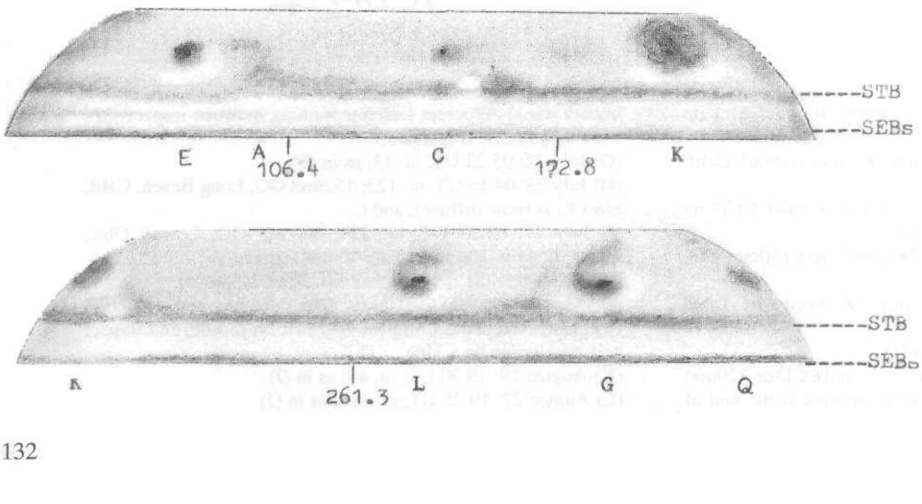

Figure 9. Strip-maps by Robert Bullen, on July 19 (20–22h UT) and July 20 (20–22h UT). Sites and λ_2 are marked below. The first site, E, was described: 'Its darkness was astounding, much more pronounced than I ever imagined.' The last site shown was Q1 at its first rising.

and further south than pre-existing impact sites, and this was apparently because the dark arc on the south-preceding (Sp.) side was already prominent whereas the black core at the north-following (Nf.) end would become more prominent over the first day or two. This may also be why sites E and H showed an apparent sharp increase in longitude over the first day or two. For site G, Rogers found that both the core and the ejecta arc intensified over the first two days (see Table 5 and Figure 4). Likewise, site A appeared more prominent when one day old (Figure 5) than in HST images on its first passage.

Early development of the dark clouds

In the first few days, an impact site typically consisted of a diffuse Sp. dark arc (the ejecta crescent) and a compact Nf. black core (the explosion site) (Figure 1D). This structure was clearly resolved for the larger sites (G, K, L). For the smaller sites, the ejecta arc was only resolved as a small blur in the best drawings and images (sites A, C, E, H, Q1) or not at all (sites D, R). HST images confirmed that there was a distinct ejecta arc for sites A, E, and Q1, but little if any for the smaller sites.[7] The visibly dark material was high in the stratosphere.[14] The ejecta arc was all at this altitude, but the black core is believed to represent a 'depot injection' of dark material at the site of the terminal explosion which continued to waft up to the stratosphere for at least several days.

After the first day or two, both the ejecta arc and the black core became more or less deformed, as described below. The dark scars were always very dark even when at the p. or f. limb, from their first rising onwards. They were never observed to fade towards the limbs. This was consistent with the high altitude of the dark material.

The colour of the dark scars, both initially and later, appeared to be neutral – black becoming dark grey. A few observers recorded them as brown, but they often suspected that this was due to the planet's low altitude; to most observers the scars were less brown than the planet's normal belts. The best direct colour photographs were by Bruton[5] and they showed the sites black or grey, not brown. Miyazaki's high-resolution colour CCD composites showed the impact sites as neutral grey, like the darkest streaks of STB and SSTB, in contrast to the browner background tone of the S. Temperate region and other major belts, especially the orange-brown SEB and NEB.

Some HST images showed the impact sites as brown – clearly redder than the grey STB and SSTB features, although not so red as the SEB, NEB, and NTB(S). This apparent discrepancy between HST and BAA observations may be due to the filters used by HST, which were at about 336nm (near-ultraviolet), 410nm (violet), 540–555nm (green/yellow), and 953nm (near-infrared).[7] Therefore many HST colour images were made from violet, green, and near-IR, in place of blue, green, and red. This may enhance any reddish tint (see spectrum in ref.14) and alter the colour relative to Jupiter if the shapes of the spectra are different.

No effects were seen from the 'dud' impacts, except that two American observers reported possible effects of impacts B and F. Hernandez reported a large ring-wave immediately following both impacts (see below). Troiani noted a tiny dark spot near the site of impact B on July 18 and 20. However, in view of the absence of these impact sites in other observations, the features seen were probably not impact-related.

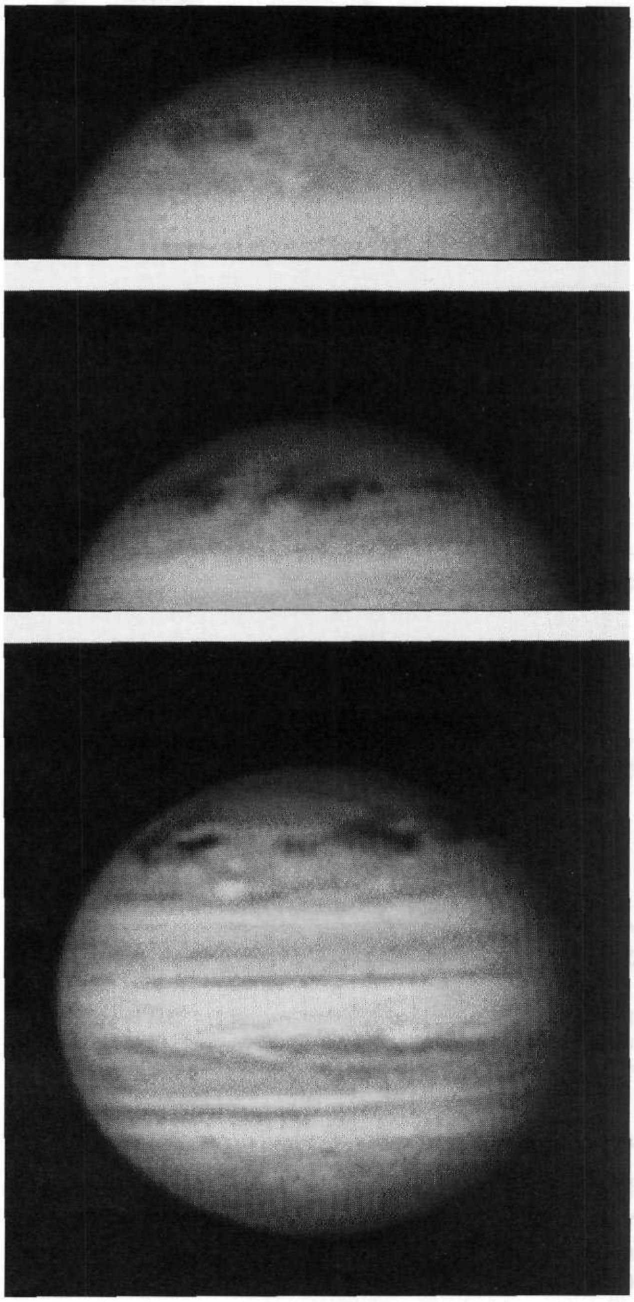

Figure 10. The three great complexes after one week. CCD images by Isao Miyazaki, Okinawa, Japan, using a 400mm reflector.
July 24: 13.06 UT, ω_2 234. Sites K/W and L.
July 25: 11.06 UT. ω_2 311. Site L on p. side. The G/D/S/R complex across central meridian; the very dark N/f. component is resolved into a pentangle of black spots which may include nuclei D, G, S with R following. Site Q1 on f. side.
July 27: 11.02 UT, ω_2 249. Sites K/W and L. The black core of the site K/W is now clearly double, possibly because of delayed intensification of nucleus W (compare July 22 and 24). North of it are 3 pre-existing white ovals, viz. f. end of 'SSTBZ' (37.5°S), SSTB white oval (40.5°S), and oval FA (33°S). Site L has emitted a dusky patch preceding it and long streamer to the south; it spans latitudes 42–66°S.

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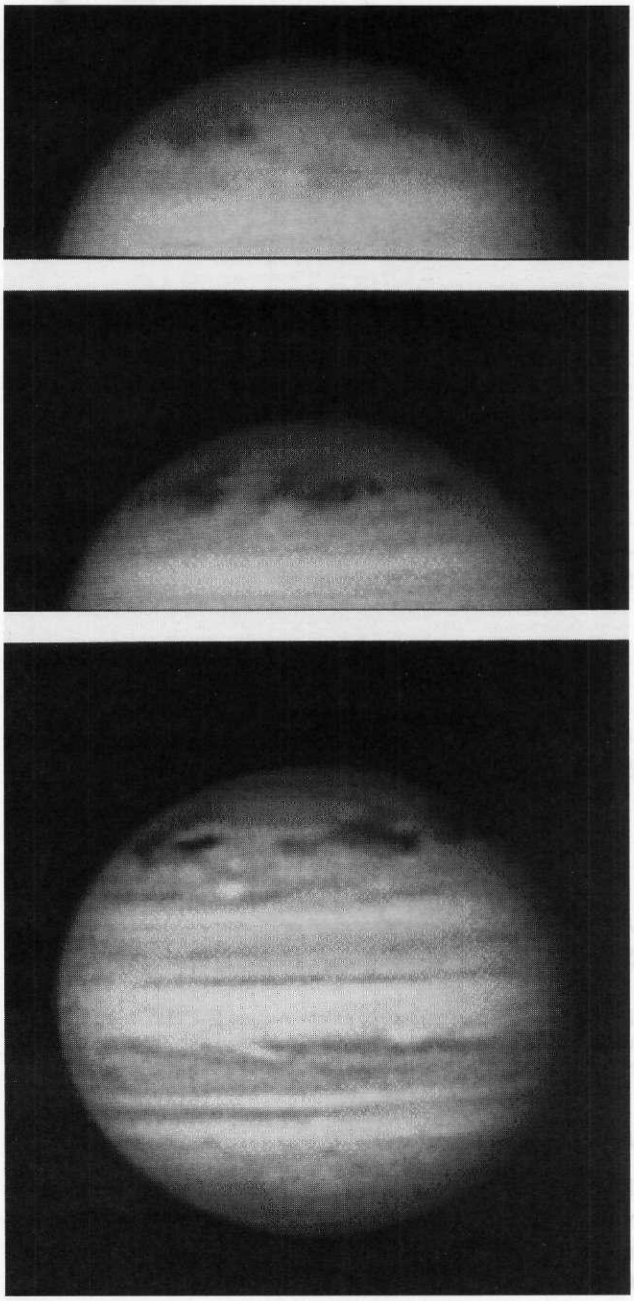

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measured, was a tiny point at the extreme Nf. end of the initial 'black core' seen from Earth.

Some sites seemed to show sudden increases in longitude of several degrees after their first passage (notably E and H), apparently because the Sp. ejecta cloud dissipated while the Nf. black core intensified.

(ii) Observers' scatter and personal equations: Initially there seemed to be great scatter (up to 10°) among visual transits, even by experienced and consistent observers, and the highest values matched the image measurements. Therefore, for the more regular observers, personal equations were deduced from comparison with measurements from high-resolution images during impact week. This showed that both personal equations (ranging from −5° to 0) and scatter (s.d. for an individual ranging from ±1° to ±3°) were about twice what is usual, probably due to the high latitude of the impacts.

For the chart, personal equations of more than 2° were subtracted, and most less-regular observers were excluded, leading to good agreement between observations. However, after impact week, transits are included from some visual observers not corrected for personal equation because they did not produce enough data in impact week; some may transit up to 5° early.

Drift rates: Results and discussion

The measured longitudes are plotted in Figure 12 and drift rates are derived in Table 3.

The overall average drift was not significantly different from the SSS Temperate Current or System III. However, there was large variation, and possible trends may exist. Firstly, some sites seemed to show idiosyncratic local motions. Secondly, the compact cores may have drifted systematically slower, as listed in the 'early' columns of Table 3. Thirdly, the more extended and evolving clouds often drifted faster, as listed in the 'late' columns of Table 3.

(i) Apparent local motions

Sites H and E: initial sharp increase in longitudes (not included in Table 3). (The shift of E was evident from the spacing of sites E, A, and C; it had been equal in the HST image of July 17[8] but was obviously unequal when seen on July 19.) This was probably due to intensification of the Nf. black core (see above).

Site H: the dark core of H extended northwards to 38°S (Figures 22 and 24). Images by Parker showed that it was attracted to an anticyclonic oval at 41°S, as also noted by the HST team.[7]

Complex sites K/W and G/D/S: rapid increase in longitudes of cores. This may have been an effect of the nearby retrograding jetstream on some cores (see below), but in G/D/S, it could also have been due to confusion caused by the successive impacts, or due to random local drifts.

P. end of site K: rapid decrease in longitude. Although other sites also prograded rapidly (see below), K was unusual in having a distinct p. patch that straddled the prograding jetstream at 43.6°S (late July), and later (late August) its p. end prograded as a rather narrow, tapered band along this jet latitude (ref.5 and Figures 14–16). This was the only clear example of a site entrained by a normal jetstream.

Minor dark areas preceding sites H and L: detached from the main sites, as described above. Both prograded rapidly.

It appears that the cloud-top prograding jetstreams (Figure 1C) had only partial influence on most visible impact sites. Although the detached spot Sp. site H (54°S) may well have been prograding under the influence of the jetstream at that latitude (53°S), it was not obviously sheared by the jetstream, and the rapidly prograding patch p. site L (46°S) did not lie on a jetstream. Rather, these seem to be extreme examples of the prograding stratospheric current (see below). Moreover the northwards extension of site H crossed over the 43°S jetstream but was not visibly entrained by it.

(ii) Slow early drift rates for compact sites or cores of sites

These black cores apparently marked deep injections of black stuff, which continued to convect upwards for days or weeks until the core dissipated. Presumably their rotation periods are those of the levels at which the comet fragments exploded. The rotation periods close to System III are regrettably uninformative, because in this particular latitude all tropospheric levels and scales are expected to show this same rotation period: the smallscale cloud-top texture observed by *Voyager* at 48°S,[11] the local slow current which governs larger visible spots throughout the SSS Temperate domain,[12] and System III (the planet's metallic hydrogen mantle), all happen to have the same rotation period. However, the slower drifts shown by several of the cores may indicate that the atmospheric wind profile is less uniform than expected.

The slowest values were the strongly retrograding speeds for the cores of complex sites K/W and G/D/S, which might have been due to the successive impacts. However, these and other black cores may also have been affected by the weak retrograding jetstream at 49°S. Later impacts were progressively further south, closer to this jetstream.[2] The last isolated impacts, Q1 and R, at 48.0°S, produced compact cores with $\Delta\lambda_2$ = −5 and −6 (near-stationary in System III). The next impact, S, went into complex G/D and an analysis of that complex is in Paper III. The last impact, W, at 48.1°S, went in <5° from impact K, so their black cores were initially unresolved, both visually and in Miyazaki's CCD images on the first passage after impact W. However, Miyazaki's images showed the black core gradually split in two during July 24–31 (Figures 1E & 10). The speed of $\Delta\lambda_2$ = +28° per month (Table 3) represents the Sf. half, measured at 47.5°S; the smaller, Np. half had $\Delta\lambda_2$ ~ +2 (not listed), at 46°S. Possibly these were the cores of sites W and K respectively, site W being further south and thus more influenced by the retrograding jetstream. However, in view of our measured latitudes and the general

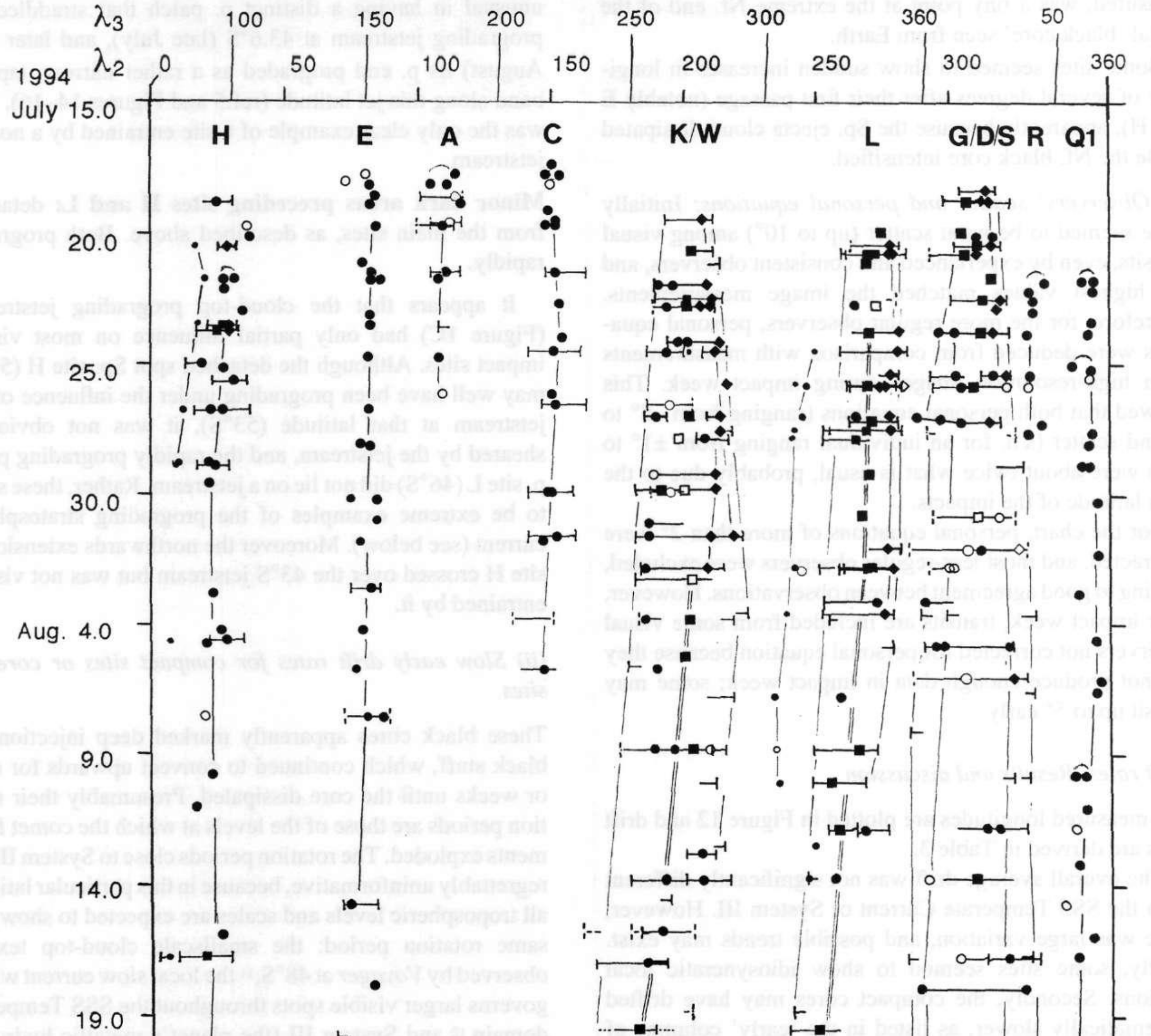

Figure 12. Chart of longitudes versus time for the dark scars. Longitudes are plotted in System II, with System II scales added. ● dark spot; ◆ black core near Nf. corner; ■ centroid of large complex; |—| p. and f. ends. Bars indicate extent of feature (these are not error bars). Open and dotted symbols are imprecise. Data are both from transits by selected visual observers (corrected for personal equations; see text), and from CCD images. See text for further longitudes in September.

complexity of other black cores as resolved by HST, the splitting of the K/W core may just have been a local peculiarity.

Reversal of drifts may have occurred when the black core dissipated, though the correlation in visual data is only loose (Table 4), and some sites showed no change in drift. The incomplete correlation could be due to inadequate resolution. Earth-based observers could not be precise about the duration of the black cores, because we could not resolve the true cores as well as HST, and our resolution diminished week by week as the planet sank in the twilight. The HST sequence of site A shows its core dissipating within 5 days. Other sites lasted longer, visually. Site C reversed its drift several days after the black core apparently dissipated, but site K several days before; for site L the times may have been close. In the largest complex, G/D/S/R, the f. part remained darkest for longest and maintained a slow drift, possibly indicating that the multiple core persisted for well over a month.

(iii) Faster drift rates for p. ends and for the whole sites as they got older

Apart from the G/D/S/R complex, the faster speeds averaged around $\Delta\lambda_2 = -19°$ per month, with p. parts of the K and L complexes at $\Delta\lambda_2 = -25$. This is similar to the SS Temperate Current (Figure 1C), but as that current operates within latitudes 38–42°S, it seems unlikely to be relevant as most sites did not extend north of the prograding SSSTBn jetstream at 43.6°S. Nor is this jetstream itself likely to be the cause of the prograding motions in most cases, as argued above; for most sites, the main regions measured were close to the impact latitudes in the SSS Temperate domain.

Instead, these rapid drifts probably represent a stratospheric current. It is possible that the high speeds were induced by energy input from the impact sites themselves, and there was an intriguing tendency for most sites to drift away from the greatest one, the G/D/S/R complex.

Table 4. Evolution of the dark impact scars

Site	*Date appeared*	*Date core last seen*	*Date fading*	*Date last seen*	*Description*
A	July 16	–	July 18	July 26	Soon became diffuse and faint. Invisible, July 29.
C	July 17	July 19	July 21	Aug.7	Small with tiny black core; July 19-21, evolved into dark E-W streak; gradually faded into 'impact belt'. Invisible, Aug.15.
K/W	July 19-22	Aug.5	Aug.8	Sep.26*	Very large and dark. Already 2 components on July 20. July 22–Aug.5, three very dark components (Np., extended to N; Nf., still black; S., fading). Then changed into long dark belt segment like NEB. Ends varied in darkness after Aug.13. After Aug.27, p.end was a long dark prograding streak.
X (p. L)	July 24	–	–	Aug.12	Faint spot, same lat. as impacts, prograded from p. end of site L. Aug.3–12, faint spot Sp. site L.
L	July 19	Aug.1	**	Oct.11*	Very large and dark. Hi-res showed long dark streamers. Merging with G/D/S/R by Aug.25. 'Irradiating spot' to S on Aug.29/30.
G/D/S	July 17-21	Sep.4	**	Oct.24*	Very large and dark and complex. Multiple spots, grouped into major Sp. and Nf. components which persisted (Nf. one still almost black on Sep.4). Long streamers and light spots developed to S.
R	July 21	July 27	**		Tiny black spot, not resolved from G/D/S after July 27.
Q1	July 20	Aug.9	July 27	Aug.28*	Black 'moon shadow' till July 27. Tiny black core persisted in dark spot till Aug.9, only modest diffusion. Then gradually became just a vague E-W streak within 'impact belt'. Condensation possibly survived in September.
X (Sp.H)	July 21	–	–	July 28	Faint diffuse patch derived from ejecta of H.
H	July 18	Aug.7	July 25	Sep.2*	Black core extended to N, July 21–28; then extended E-W instead; diffuse and southerly by mid-August; then just a condensation on 'impact belt'.
E	July 17	Aug.2	Aug.2	Sep.2*	Black 'moon shadow' till Aug.2; gradually faded into dusky E-W streak on 'impact belt'.

†This column gives the date on which the black or nearly-black core was last seen (visual or CCD).
*These sites still dark thereafter, but merged into impact belt.
**Few late high-resolution views so timecourse of fading uncertain.

However, the steadiness of the drifts after July suggests that they may actually represent a permanent stratospheric wind.

Evolution of the impact scars

The visible evolution is described in Tables 4 and 5 (and ref.5); see Table 6 and Figures 13–24 for more details. Fading of dark areas began after 2 days for site A, but only after 3 weeks for the largest sites. Meanwhile the black cores in several cases showed idiosyncratic local motions, while overall the sites tended to extend in longitude, and grey patches appeared outside the previous boundaries of some sites. The main smearing was in the east-west direction. But from the largest sites L and G, long streamers extended to the south, to 66°S from site L (Figure 10), while the north edges remained at 43°S in most cases. By late August, sites A and C had disappeared, and sites Q1, H, and E were reduced to indistinct condensations on a dusky 'impact belt' which extended all round the planet at the impact latitude. However, the three largest complexes (K/W, L, G/D/S/R) remained very large and dark.

The sites were still just as dark when near the p. or f. limb. Indeed, they were sometimes reported to be even more conspicuous near the limb than when full on the disk. This seemed to be the case for the diffuse streak of site C in early August, and was also reported for other sites: Q1 on Jul 30, E on Aug 7 & 14, K on Aug 15 (Rogers); K on Aug 5 (Heath); Q1 on Aug 13 (Murugesh). They were still generally seen as grey.

Eventually, in August, the sites began to merge into a planet-circling 'impact belt'. As the planet was sinking into twilight with the disk size decreasing and the seeing generally worsening, this appearance was first seen by low-resolution observers, but in September it was confirmed by higher-resolution observers. The three greatest complexes began to overlap to form a massive dark belt like the NEB covering K/W/L/G/D/S/R, whereas in the other hemisphere, a fainter, narrower belt linked the remnants of sites Q1/H/E/A/C.

Table 5. Intensity estimates

Site:	*E*	*A*	*C*
July 17		5½	4½
July 19	9–10	3½	
July 28; 29	(≥9) ;	–	2½
July 31	(>6)	–	
Aug.5	4	–	(~3)
Aug.7	~6		
Aug.19	~4		

Site:	*K*	*L*	*G*	*Q1*	*H*
July 18	–	–	5–6, 9–10	–	5
July 20; 19	7–8, 10	8–9, 10	8, 10	–;	6
July 23			7–8, 10	10	8–9
July 25		9	9, 10		
July 29; 28	7½–10;			(≥9)	
Aug.1; 7	7–8, (10)	8, (10)	P=9;		>6
Aug.8; 9	7–8	9;	F=9–10	≥9	(~5)
Aug.15; 14; 19	6–7;		F≥8;	~3	~3
Aug.25; 28	3½	6;	P=6, F≥8		

Footnotes to Table 5

These estimates by Rogers are on the usual scale from 0 (brightest) to 10 (black). The belts were estimated as follows during this period: SEB, 3½–5; NEB, 6–7½; NTB, 3–5½. Values separated by a comma are for ejecta arc and black core respectively. Values in brackets are rough estimates derived later from drawings.

Some intensity estimates were also provided by Colombo, McKim, Cuppens, and Schmude, but are not tabulated as they did not comprise consistent long series. Colombo rated sites K, L, and G as intensity 8–10 during impact week.

Also, Hernandez rated sites K, L, and G on the American scale which we have converted to the BAA scale by subtracting from 10, giving the following intensities. July 22–31: 10 (core) and 7–9 (linking streaks). Aug.1–22: 10 (main part of each site). Aug.30–Sep.18: 9–10 (developing impact belt).

Development of global impact belt

The new belt did not form simply by the steady spreading of the impact scars. Rather, as the distinct scars spread and faded, a narrow but diffuse belt gradually materialised between them, in about the same latitude as the original impact clouds.

(i) From E to K: There was a distinct narrow (S)SSTB along here at the time of the impacts, at 43°S, forming the S edge of a bright strip of SSTBZ which had been tracked for 2 years. So the time of origin of an impact belt in about the same latitude is uncertain. Sites A and C seemed to dissolve into one by mid-August, and by early September there was a uniform narrow dark belt all along here which seemed darker than before the impacts, merging imperceptibly into the advancing p. end of site K.

(ii) From K to R: The three great sites remained distinct, but the space between K and L was interrupted first by grey patches detaching from L, then (Aug.22) by a weak southerly belt connecting them. The narrower space between L and G was highlighted by a bright spot in late August, but by August 25 a dark belt segment connected the two sites. By Sep.18, the whole sector K/W/L/G/D/S/R was a massive dark belt like the NEB.

(iii) From R to E: A narrow grey impact belt was evident from G/D/S/R through Q1 to H as early as Aug.11–14. (Site Q1 was a small dark condensation in it; H a longer, more southerly streak.) By late August it was fairly continuous and Q1 inconspicuous. Sites H and E were both long east-west streaks by mid-August, but there was no belt connecting them (except a very faint pre-existing line), even as late as Aug.26. (However, Miyazaki's methane image on that date[5] does show a light impact belt between them.) On Aug.31, Hernandez drew an impact belt running through site E, and thereafter he drew a continuous, but uneven and undulating belt throughout this sector.

Although the sites did not spread evenly to form the new belt, it is likely that the belt material did all come from the visible sites, perhaps in the form of a thin layer at a different altitude from the main clouds, or perhaps by irregular (unresolved) fragmentation similar to the emergence of the cloud p. site L. The alternative – that the impact belt came from a prolonged drizzle of smaller impacts after the main impact week – is unlikely, first because no such impacts were recorded by HST or infrared observatories, and secondly because the known minor impacts (B, F, etc.) did not produce dark material visible from Earth.

Observations in September and October

Observations after early September, when the individual sites merged, are not listed in Table 6 or Figure 12. The main reports were as follows.

Hernandez:

Sep.3/4, ω_2 302: Major but irregular impact belt, with last major blob at λ_2 =319 (Figure 20).

Sep.6/7, ω_2 32: Continuous undulating impact belt; condensations may be Q1, H, E?

Sep.9/10, ω_2 116: Again a narrow impact belt across whole disk; darkens at λ_2=110, leading up to dark and spiky complex K at f. limb.

Sep.17/18, ω_2 234: Massive black impact belt (Figure 20).

Sep.18/19, ω_2 360: Continuous undulating impact belt; condensations may be Q1, H, E?

Devadas & Murugesh:

They continued to make frequent drawings until late October. They always drew a long dark impact belt, fairly narrow, either double (Devadas; narrow impact belt plus SSTB?) or diffuse (Murugesh) (Figure 26). Sometimes sectors were missing. Devadas usually drew the belt darker at the p. and/or f. limb; Murugesh only sometimes drew this effect.

Their drawings agree with Hernandez' reports, and with Bruton's colour photo of Aug.23 (ref.5; major impact belt with f. end at λ_2=328, then narrower impact belt with condensations at λ_2=345 and following). This f. end remained at λ_2~330 for at least another month, and the belt was faint from there to λ_2~100–140.

Their transits and estimates of longitudes were as follows:

(i) P. end of darker section (site K): λ_2 = 153 (Sep.2); dark condensation, 142 (Sep.26).

(ii) P. end of darker section (site L): 210 (Sep.17); (~205) (Sep.22); 197 (Oct.11).

(iii) F. end of very dark section (G/D/S/R): 332 (Sep.13); 334 (Sep.25).

(iv) F. end of impact belt (diffuse, tapered): (~10) (Aug.27, Sep.6 & 11; continuous by Sep.23).

Devadas' colour estimates in this period were as follows. SPR and impact belt appeared brown, becoming light brown or even orange. NEB appeared brownish-red; NPR, grey. (However on Sep.4, Gross, using the 1-metre reflector at Puimichel, saw the continuous impact belt as grey in contrast to the brown SEB and NEB, and this accords with Bruton's photograph of Aug.23.[5])

After Oct.9 Devadas no longer drew the impact belt darker near the limbs, except for drawings on Oct.23 (f. limb) and Oct.24 (p. limb) which implied that the region of complex G, λ_2~250–290, was still darker. The impact belt was still evident in his last drawing on Oct. 29, just 3 weeks before solar conjunction.

Long-term significance

Stratospheric currents

Our longitude measurements have revealed a surprising variety of currents influencing the impact clouds, which were discussed in detail above. Before we can interpret these drifts properly, we will need to understand better how deep the various visible components lie, and how the impact energy itself may have altered the local winds. But it does appear that rapid prograding drift was a rather general phenomenon of the more extended impact clouds, and this may have been due to a permanent stratospheric current.

Duration of impact belt in 1995

The impact phenomenon did not end in 1994. The impact belt was still present in the 1995 apparition,[5] initially as dark as it had been in 1994 September. In 1995 February it appeared to be fading. From March to May it remained prominent around half its circumference, though now less dark than the NEB and SEB; this sector was the remains of the great sites from K to G. Around the other half of the planet, where the weaker impacts had occurred, the impact belt was by then indistinct or absent. As of mid-1995, it is becoming difficult for visual observers to tell whether there is a persistent impact belt or just a strong but 'normal' SSSTB. In the light of HST images taken in 1995 February,[15] it seems possible that impact smoke has settled from the stratosphere down to the normal cloud-top level, where it is now just an added pigment in the normal belt region.

This timecourse for disappearance of the impact smoke is consistent with the modelling by R. A. West and colleagues,[14] based on HST imagery in 1994. They showed that changes in the first month were due to coagulation of particles, not sedimentation, and that the small smoke particles could stay aloft for months to years, but would settle out much faster as they progressively coagulate.

Does dark material persist to contribute to normal belts?

If the impact smoke is indeed settling down into the normal belts, how long will it last? On the one hand, it could disappear within months, if the particles continue to sink deeper, or if they are chemically destroyed. On the other hand, one should consider the possibility that the smoke could last a very long time, perhaps contributing to the normal darkness of the jovian belts. It is not known what the brown and grey substances of the normal belts are; could they include smoke created in rare but long-lived comet impacts, thoroughly mixed into the upper troposphere? The material would probably have to last for millennia, which seems unlikely, as there is evidence that the jovian troposphere recycles down to a level where the temperature is ~1000°K (ref.12); one would probably require silicate grains to survive such heat, and they would be too dense to remain in the clouds. However, perhaps it would be worth investigating whether some cloud material might avoid such extreme thermal cycling, and permit the long-term survival of dark particles from impacts.

No such impacts have been observed before[16]

The SL9 impact sites were unprecedented in their size, blackness, sudden appearance, and shape. The author recently surveyed all available observations of Jupiter,[12] which cover the planet continuously since 1878 (apart from solar conjunctions). Almost all dark spots are of recurrent types in fixed latitudes belonging to permanent currents; their typical forms, circulations, and lifetimes are well established. Although some of them, notably NEBs projections and South Tropical Disturbances, can occasionally be almost as large, dark, and rapidly evolving as the SL9 impact sites, they are clearly recognisable as meteorological features. There are no outstanding records of large black sudden-onset spots which cannot be attributed to these categories, and none which resemble the large SL9 sites in detail.[16] So we can definitely conclude that no impact on the scale of SL9 fragments G, K, or L has ever been observed before, and the frequency of such impacts (allowing for unobservability during solar conjunction) is less than one per 80 years.

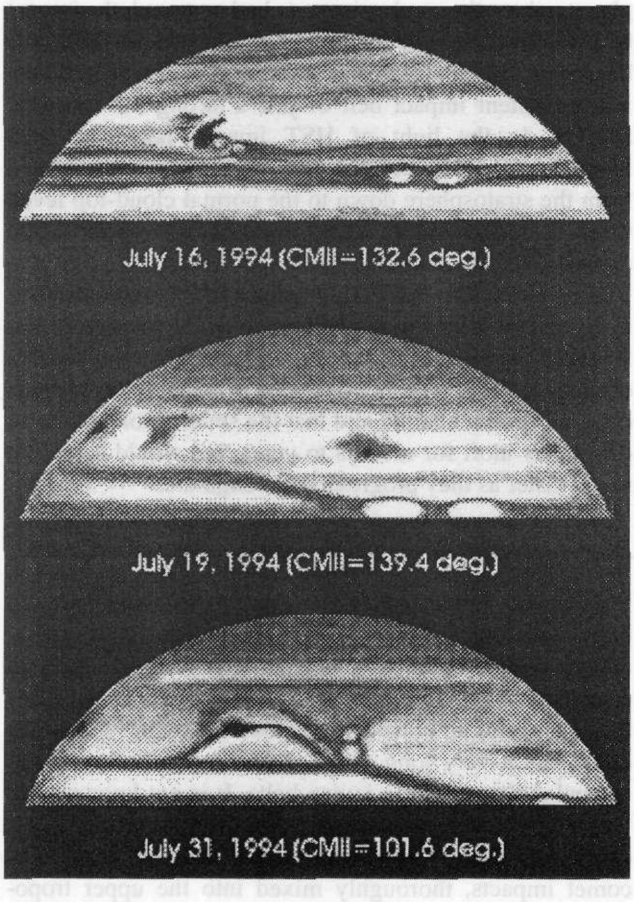

Figure 13. Evolution sequence of sites A and C: Carlos Hernandez (Florida). Drawings by J. Beish (July 16) and C. Hernandez (July 19 & 31), using a 410mm reflector. Ovals BC and DE on f. side.
July 16/17: 23.35 UT, ω_2 113. First distinct visual sighting of Site A on its first passage. Hernandez made a similar drawing.
July 18/19, 01.25 UT, ω_2 139. Site E on p. limb; site A fading; site C south of oval BC.
July 30/31, 00.20 UT, ω_2 102. Site E has a black spot; site A almost disappeared (the small bright oval and shading to the north, on CM, are pre-existing features of SSTB); site C now a faint streak near f. limb.

Acknowledgments

I am very grateful to all the observers and coordinators who contributed (Table 2). Thanks go especially to P. Devadas, Carlos Hernandez, and Isao Miyazaki, for their very extensive contributions, and to Mark Bosselaers for the prolific observations and analysis from the VVS (Belgium). I also thank James Lancashire and Michael Foulkes for their help with this report.

Address: 10 The Woodlands, Linton, Cambridge CB1 6UF

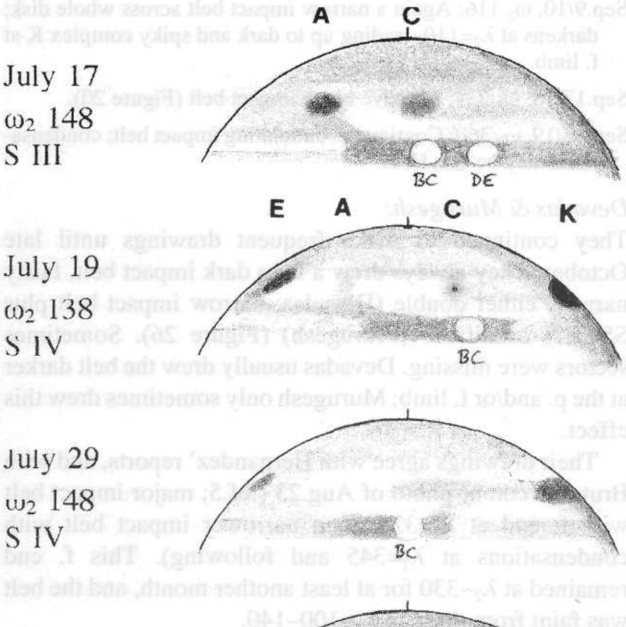

Figure 14. Evolution sequence of sites A and C: John Rogers (Cambridge, England). All drawings were by John Rogers using the 310mm refractor at the Institute of Astronomy, Cambridge, England, around 19–21h UT on the indicated dates, except on August 27, which is by James Lancashire using the same telescope. Seeing in this and later sequences is given on the Antoniadi scale; note that later drawings are generally at lower resolution. This sequence shows sites E, A, C, K.
E: near p. limb; gradually fading.
A: already fading by July 19 and disappeared by July 29; note SSTB patch near that longitude.
C. south of oval BC; evolves into a dusky streak which gradually fades into an 'impact belt'.
K: on f. limb. On July 29, note light patch south of K. On Aug. 5, what looked like a fireball on the limb was actually Ganymede emerging from occultation! On Aug. 27, the p. end of site K has advanced to much lower longitude.

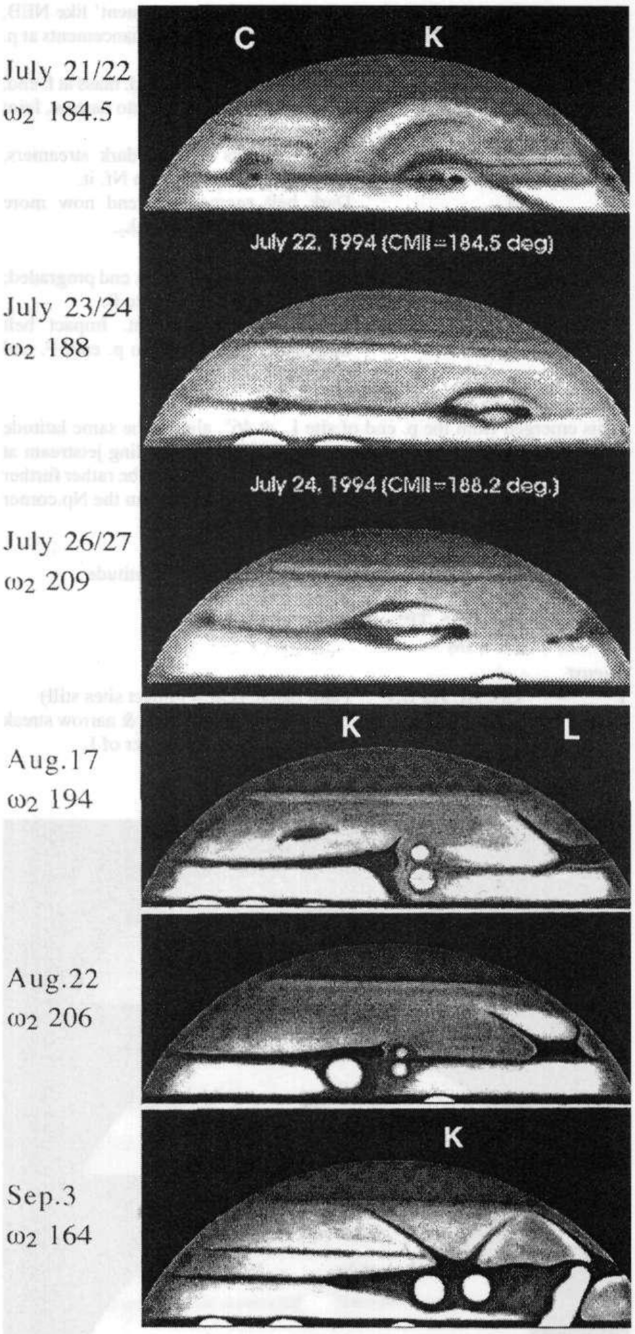

Figure 15. Evolution sequence of site K/W: Carlos Hernandez (Florida). Drawings with a 410mm reflector till August 1, 200mm reflector thereafter. These drawings show the great site K/W near centre, with site C fading towards p. limb, and great site L on f. limb. Bottom of each drawing is in the middle of the STB, which is interrupted by ovals BC and DE (N. of site C) and FA (Nf. site K).
July 21/22: 00.10 UT, ω_2 184.5. Site K seems to have multiple dark nuclei and multiple arcs to the south (before the W impact). Site C on p. side.
July 23/24: 01.55 UT, ω_2 188. Site C and K/W developing.
July 26/27: 00.00 UT, ω_2 209. Similar to the above.
Aug. 17: 02.00 UT, ω_2 194. Site K/W has become a long very dark belt segment, 26° long by transits; the southern arc has almost disappeared. To its north is the pre-existing bright strip of SSTBZ with a dusky 'bridge' and bright oval at its f. end. Site L on f. limb has some projections from its p. end.
Aug. 22: 01.30 UT, ω_2 206. Similar to Aug. 17. Bright area south of site L near f. limb.
Sep. 3: 00.20 UT, ω_2 164. Site C is no longer distinguishable; site K/W has merged with the 'impact belt' p. it and is also connected to site L on f. limb. Long streamers to south. Site K/W is decreasing in longitude at about the same rate as the bright ovals and dark veils to north, which appear to be the pre-existing SSTB/STB features moving with the SSTC. STB (at bottom) is interrupted by ovals BC and DE on p. side, FA on f. side.

Appendix 1. Detailed history of the visible impact scars

Table 6 summarises the appearances recorded at moderate to high resolution. (Many other observers saw the sites at lower resolution, including Patrick Moore and Paul Doherty who probably saw site A on its first rising.) Sites are listed in order of increasing longitude.

Table 6. Evolution of the visible impact scars

Abbreviations

Dates in July are given in decimal form, UT.

Observations were by the following: F. Balella, D. Bruton, R. Bullen, E. Colombo, P. Devadas, D. Gray, C. Hernandez, J. Lancashire, L. Macdonald, R. McKim, H–J. Mettig, I. Miyazaki, K. Murugesh, D. Parker, T. Platt, J. Rogers, R. Schmude, D. Strange, L. Testa, D. Troiani, G. Vargas, S. Williams. *= CCD image.

Descriptions are abbreviated as: d.s., dark spot; v.d., very dark; hi-res, high-resolution; N–S, north-south; E–W, east-west.

Date	*Observers*	*Description*
***Site A** (Figures 13, 14)*		
July		
17.0	CH, DP* et al.	First passage: d.s. with S fringe
17.4–17.8	IM, SW*, FB, JR	Conspic. d.s.
18.2–19.0	DB, RS, IM, KM, GV	Diffuse d.s., smeared N–S
19.5	IM*	Core smeared E–W
19.8–26.1	many	Fainter, diffuse, smeared N–S (Nf. end involved with SSTB dark patch)
26.5	IM*	Long narrow grey E–W streak, inconspic.
29.8, 31.8	JR	Absent. (SSTB dark patch still present.)
31.5	IM*	Absent.
***Site C** (Figures 13–16)*		
July		
17.4	SW*, IM*	First passage: tiny d.s. with slight fuzz (<A)
17.8–18.6	FB, JR, DG, DB, KM	D.s., quite conspic.
19.0–19.8	CH, RS, DB, IM*, SW*, JR, RB	V.small dark core, small or faint diffuse halo
21.6	IM*, KM, PD	Dusky dark E–W streak
22.8–28.1	many	Dusky dark E–W streak
29.8	DS*, JR, RB	Faint diffuse E–W streak, extending towards K
31.0–31.8	CH, IM*, JR	Quite faint E–W streak (near f. limb)
August		
2–7	DB, IM*, JR, RS*	Dusky streak, a diffuse enhancement of narrow impact belt which runs up to site K.
15, 31	JR, CH	Faint or narrow impact belt is continuous, site C not visible.

***Site K/W** (Figures 10, 14–17)*
(Impact W on July 22.3 was 5° f. impact K according to plume timings (Table 1), but 2° f. it according to HST images of the sites.[7] Impact W did not make a perceptible difference visually, but may have been belatedly resolved in high-resolution images. The gradual separation of the two black cores may have occurred because impact W was 0.4° further south and thus more influenced by the retrograding jetstream at 49°S, or it may have been just a local peculiarity; see text. The 'dud' impact U occurred within the same complex. There was a pre-existing bright white spot just N. of site K.)

Date	*Observers*	*Description*
July		
19.5	IM*	First passage: great v.d.s. with black core, dark halo
19.6–19.8	KM, JR, RB	Great v.d.s. [Bright halo – KM. Whitish area to Nf. on f. limb – JR]
20.8	many	V. large, v.d.s.; black core; dark condensation in p. part. [Bright w.s. to N near p. limb – JR]
20.5, 21.2, 22.0	SW*, RM, CH	Black core now streaked p.; Sp. arc now a conspic. E–W streak

22.5	IM*	Huge dark cloud Np.(sic) from black core; conspic. E–W streak to S.
22.8–31.5	many	Three v.d. components within great complex: Np. (extending N of impact lat.; irreg. at hi-res.), S. (derived from ejecta arc; becoming fainter), and Nf. (black core; becoming double in hi-res. images). [Light patch to S. on f. limb – JR]
31.5	IM*	Nf. d.s. now double (see below). S. d.s. now fainter. Np. d.s. conspic.; small wisp (?detaching) from p.end may be beginning of impact belt.
Hi-res details of black core		
22.5	IM*	Single black core (first passage after W)
24.5	IM*	Black core just resolved as double
27.0, 27.5	DP*, IM*	More elongated Np.–Sf.
31.5	IM*	Clearly resolved double black core
August		
1–5	JR, JL, DB, DT, IM*	P. and f. d.ss. are still large and v.d., connected by dark 'belt', but S. d.s. rarely seen. (P. end joins new diffuse impact belt.)

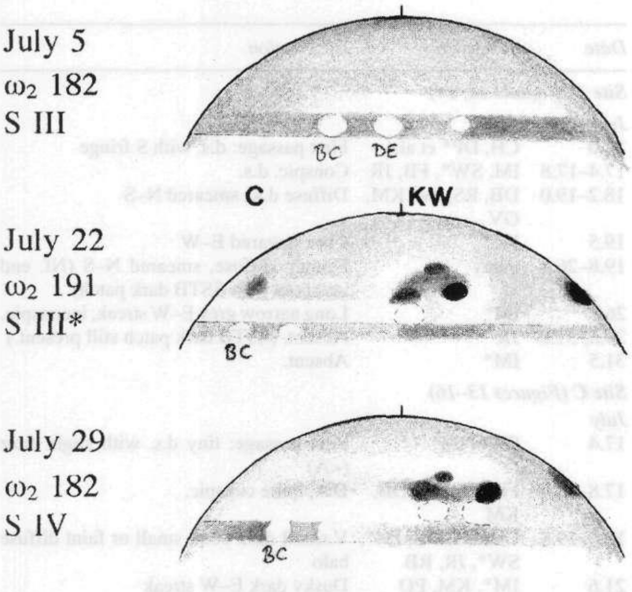

Figure 16. Evolution sequence of the site K/W: John Rogers (Cambridge, England). All drawings were by John Rogers using the 310mm refractor at the Institute of Astronomy, Cambridge, England, around 19–21h UT on the indicated dates, unless otherwise stated. This sequence shows site C (near p. limb), K/W, and L (on f. limb).
July 5: Before the impacts; note bright strip of 'STZ' (strictly, 'SSTBZ').
July 22 (drawn with 250mm reflector; details added from slightly earlier drawing by James Lancashire with 310mm refractor): site K/W consists of 3 very dark spots; a bright spot and grey shading north of it mark the pre-existing f. end of the SSTBZ.
July 29: similar.
Aug. 8: site K/W has changed into a long dark bar similar to the NEB.
Aug. 15: p. end advancing and merging in 'impact belt'; the SSTBZ white spot and shading persist to the north.

7–10	RS, KM, PD, JR, JL, DG, DB, DT	A massive v.d. 'belt segment' like NEB, ~40° long; only slight enhancements at p. & f. ends.
12–22	KM, PD, DB, JR, CH	Massive dark belt with v.d. mass at f. end, but p. end faded, tapers into narrow, faint impact belt p. it.
22	IM*	Ditto; consists of long dark streamers, merging into SSTB patch Nf. it.
27	JL	Dark belt segment; p. end now more distinct, darker, at lower λ_2.
September		
3	CH	Long v.d. belt segment; p. end prograded; two dark projections far to S.
5, 8	IM*	Long v.d. belt segment. Impact belt intensi-fies smoothly into p. end. F. end patchy.

***Extra spot p. site L** (Figures 10, 18–20)*
(This emerged from the p. end of site L, at 46°, almost the same latitude as the impacts, so it was not due to the SSSTBn prograding jetstream at 43.5°N. From Aug.3 onwards, images revealed the spot to be rather further south, but alongside it was a narrow streak running p. from the Np.corner of L; this streak may have been on the jetstream.)

July		
24	IM*	Grey streak, on impact latitude
25	FB, LT*, H–JM	Minor spot p. L
27	CH, DB*, TP*, DP*, IM*	Minor spot p. L
August		
1	CH, JR, JL, DS*	Faint patch. (Lat.= impact sites still)
3–10	IM*, JR, DB	Separate dusky spot Sp.L & narrow streak running p. from Np.corner of L
12	KM	Spot Sp. L

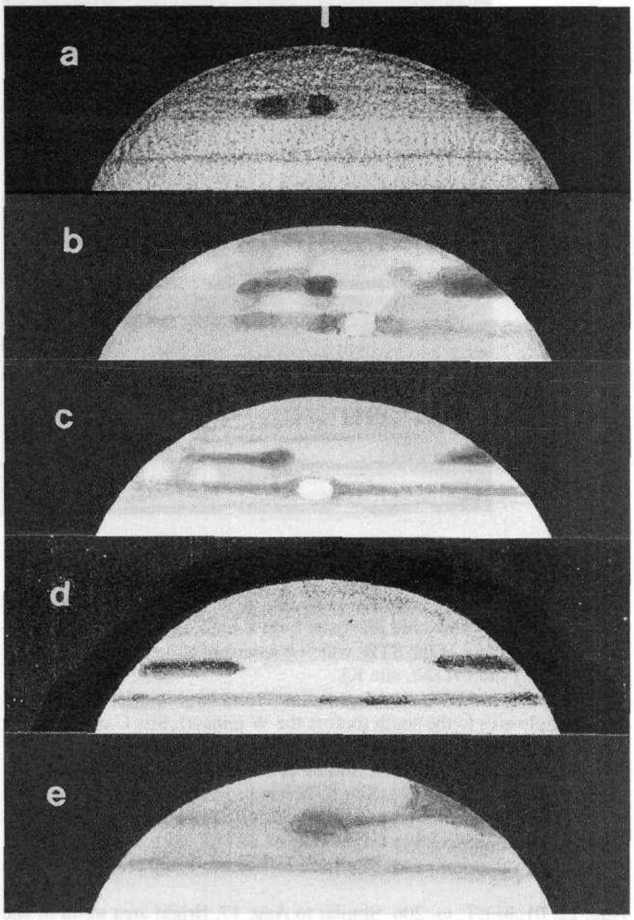

Figure 17. Sites K and L in August.
(a) Aug. 1, 19.00 UT, ω_2 208; J. Warell (Sweden).
(b) Aug. 8, 19.43 UT, ω_2 205: J. Rogers (England). (Oval FA near CM.)
(c) Aug. 12, 13.35 UT, ω_2 223; P. Devadas (India).
(d) Aug. 19, 14.15 UT, ω_2 218; P. Devadas (India).
(e) Aug. 20, 00.30 UT, ω_2 229; A. G. Vargas (Bolivia).

Site L (Figures 10, 17–21)
(The greatest isolated impact. § indicates emergence of the fainter patch from the p. end as described above.)

July		
20.0	GV, DB	First passage: great v.d.s.
20.1–22.0	many	Great v.d.s. with black core, dark Sp.arc
22.1–23.8	many	Great v.d.s. with multiple components
24.5	IM*	Like a black comet. §Faint new streak p. it
25.0–25.5	DP*, IM*	Dramatic streamers from black core to p. and to S (near p. limb)
25.8	many	Still huge and v. dark. §
27.0–27.5	DB, DP*, IM*	Dramatic long streamers from v.dark complex.§
31.2	MJanes (report on Internet)	Dramatic long streamers from complex
August		
1–3	DB, *CH*, JR, JL, DS*, IM*	S*till* huge and v.d., *like* a black comet, with black core at Nf. end. §
7–12	KM, DB, JR, JL	Still huge and v.dark. §
18	CH	Long, v.d., with streamers to Sp., Np., Sf., light areas N and S, bright spots f.
19	KM, PD	Long, dark, with bright spot f.
22–30	CH, JR, JL, DS*, IM*	Long dark belt segment (>NEB, ~30° long), *now linked to site G by broad* impact belt. [CH & IM* show bright spots N and S of this link; CH draws bright spot S. of L.]

***Sites G/D/S/R** (Figures 10, 18, 20–24, and Paper III)*
(Impact G was much the greatest in this group, and the G/D/S/R complex became the greatest dark scar of all. Impacts D and S were 7–9° f. impact G, 2° apart according to plume timings (Table 1), but 0.5° apart according to HST images of the sites.[7] Neither site was seen visually but CCD and HST images showed that they contributed to the great intensity and complexity of site G, which overlapped them. Impact R produced a small black spot 17° f. impact G, which later merged into the great complex. R and S were slightly south of the others. The site of 'dud' impact Q2 was 3° f. impact R, and was invisible from Earth although HST imaged a very tiny spot there. For details of the complicated internal evolution, see Paper III.)

July		
17.5	IM	First rising of site D: *nothing visible*

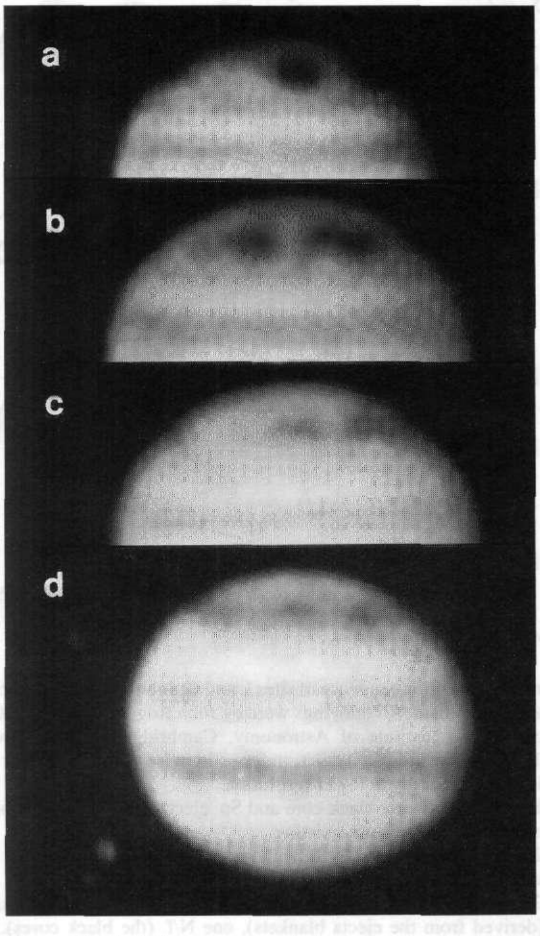

Figure 18. Evolution sequence of sites L (near CM) and G (on f. side): D. Strange (Dorset), using a 20-inch reflector stopped down to 12 inches. CCD images are 160-msec exposures, digitally unsharp-masked. From top to bottom:
(a) July 20, 20.33 UT, ω_2 263.
(b) July 25, 20.24 UT, ω_2 288.5.
(c) Aug. 1, 20.41 UT, ω_2 269.5.
(d) Aug. 23, 19.38 UT, ω_2 293.

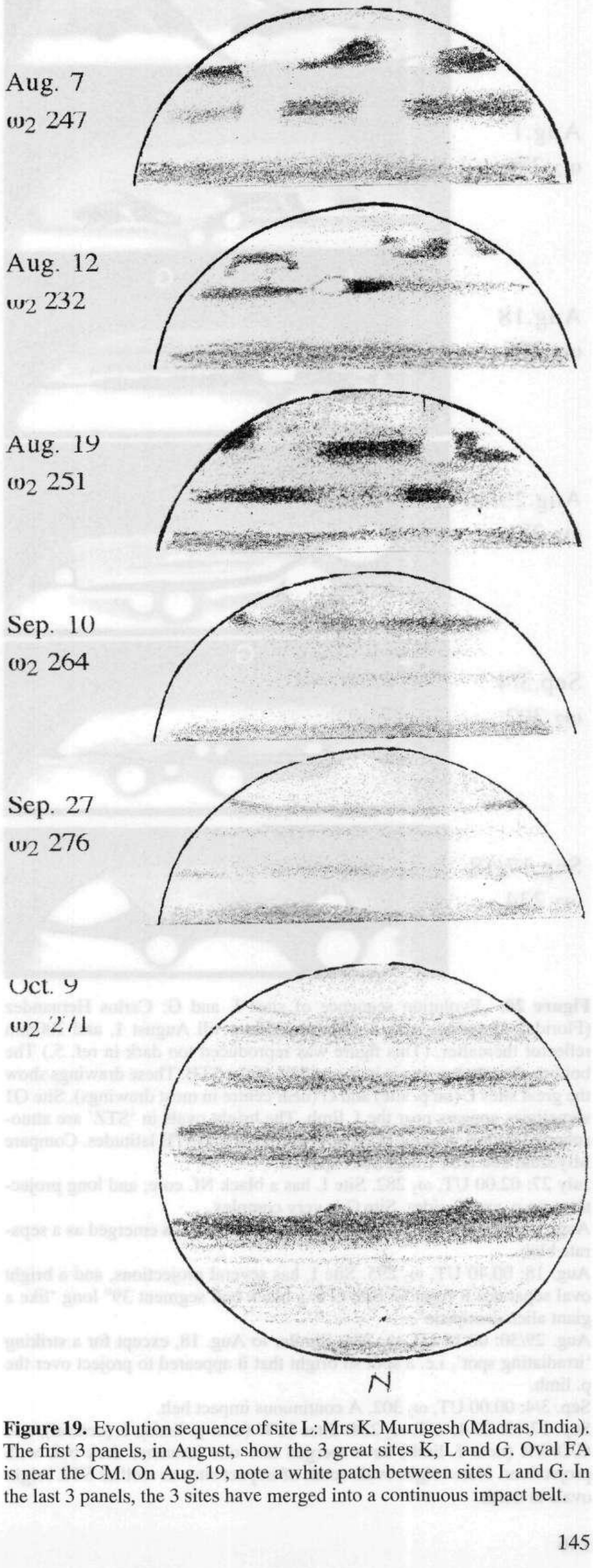

Figure 19. Evolution sequence of site L: Mrs K. Murugesh (Madras, India). The first 3 panels, in August, show the 3 great sites K, L and G. Oval FA is near the CM. On Aug. 19, note a white patch between sites L and G. In the last 3 panels, the 3 sites have merged into a continuous impact belt.

18.4	SW*, IM*	First passage of site G: great v.d.s. with black core, dark arc. Site D is visible as tiny d.s. 8° f. core of G
18.8–20.8	many	Great v.d.s. with black core, v.dark arc, surrounded by light halo in some drawings
		First rising of site Q2: nothing visible

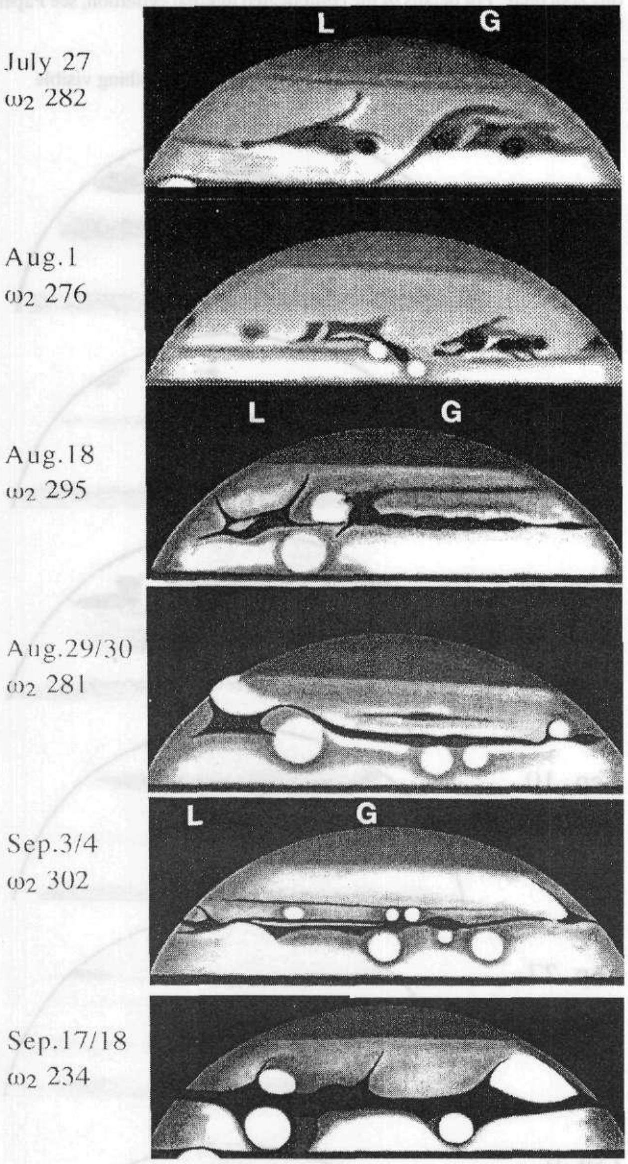

Figure 20. Evolution sequence of sites L and G: Carlos Hernandez (Florida). Drawings with a 410mm reflector till August 1, and 200mm reflector thereafter. (This figure was reproduced too dark in ref. 5.) The bottom of each drawing is in the middle of the STB. These drawings show the great sites L (on p. site) and G (near centre in most drawings). Site Q1 sometimes appears near the f. limb. The bright ovals in 'STZ' are atmospheric features in a pre-existing disturbance of SSTB latitudes. Compare Miyazaki and HST images in Paper III.
July 27: 02.00 UT, ω_2 282. Site L has a black Nf. core, and long projections on p. and S. sides. Site G is very complex.
Aug. 1: 01.00 UT, ω_2 276. The p. projection of L has emerged as a separate blob.
Aug. 18: 00.40 UT, ω_2 295. Site L has several projections, and a bright oval separates it from G. Site G is a black belt segment 39° long 'like a giant alien centipede'.
Aug. 29/30: 00.15 UT, ω_2 281. Similar to Aug. 18, except for a striking 'irradiating spot', i.e. a spot so bright that it appeared to project over the p. limb.
Sep. 3/4: 00.00 UT, ω_2 302. A continuous impact belt.
Sep. 17/18: 23.45 UT, ω_2 234. Sites K/W (near p. limb), L (central), and G/D/S/R (near f. limb) have merged into one immense dark belt with projections. Note bright ovals south of impact sites as well as STZ bright ovals to north.

21.8	FB	Second passage of site R, first passage of site S. G/D/S: V.large, v.dark, complex. R: small black spot just f. G/D/S
22.2–23.0	RM, DP*, CH	G/D/S: V.large, v.dark, v.complex R: small black spot just f. G/D/S
23.8–27.2	EC, DG, JR, DB, RM, CH	G/D/S: V.large, v.dark, complex, with two major components; Sp.(derived from ejecta arcs) and Nf.(merged black cores). R: small black spot just f. G/D/S, becoming linked to it.
30.8	JR	Still two large, v.d. components
Hi-res details		
23.0–27.5	DP*, IM*	(See Paper III.)

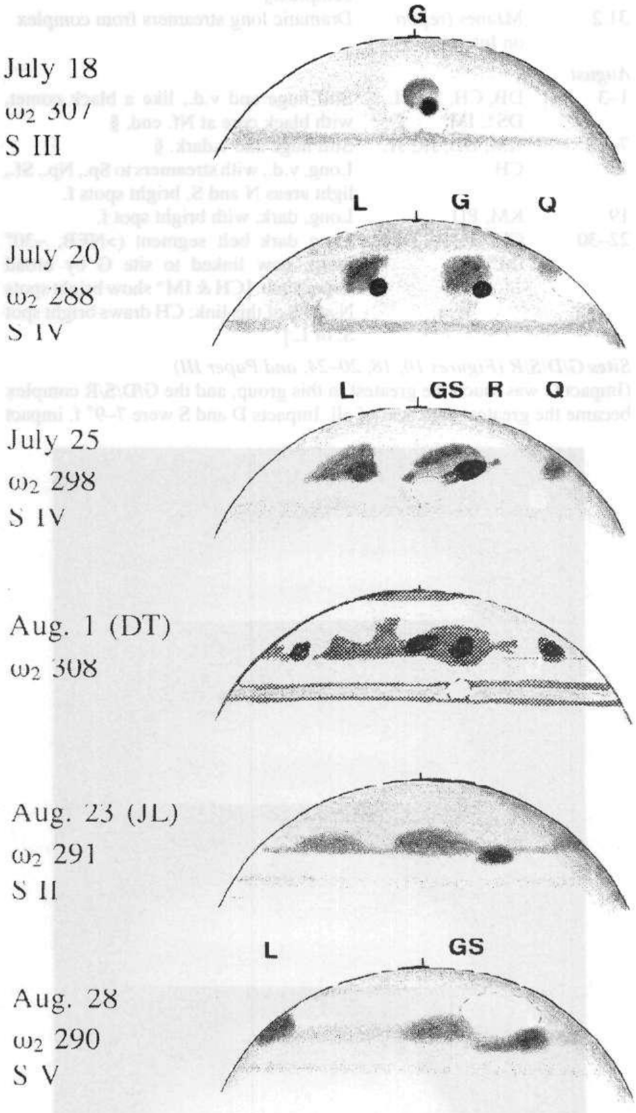

Figure 21. Evolution sequence of sites L and G: John Rogers (Cambridge, England) and others. All drawings were by John Rogers using the 310mm refractor at the Institute of Astronomy, Cambridge, England, around 19–21h UT on the indicated dates, unless otherwise stated. Note that later drawings are generally at lower resolution.
July 18: site G showing black core and Sp. ejecta arc. The double bright spot on its north edge is pre-existing.
July 20: Site G now joined by L, with site Q1 appearing for the first time on the f. limb.
July 25: Giant G/D/S/R complex already has two major components, one S/p. (derived from the ejecta blankets), one N/f. (the black cores). The white spot on its north edge has brightened.
Aug. 1, ~01.00 UT, by Dan Troiani (Illinois, USA), with 200mm reflector. The same sites present but more complex.
Aug. 23, 19.35 UT: by James Lancashire (Cambridge), 310mm refractor, copied by JR. Site D/G/S/R still consists of two major dark spots. An 'impact belt' now connects all the sites.
Aug. 28: Shows the same as Aug. 23, with a large light area south of site D/G/S/R, which was not apparent when closer to the central meridian.

August

1–4	JStuckey*, CH, DB, DT, JR, JL, IM*, PD	Massive v.d. belt segment with several condensations
6	JStuckey*, DT	Massive v.d. belt segment, ~40° long, with long streamer from p. end to Sf.
6	IM*	Many v.d.ss. in mass at f. end
11–20	CH, IM*	V.d. belt segment ~40° long, with several condens'ns, and almost-black mass at f. end
14, 16	JR, CH	[Bright area Sf.]
23–26	DB*, IM*, H–JM, JR, JL, DS*	Still a massive long v.d. belt segment, with almost-black mass at f. end. Now embedded in longer impact belt
28, 30	IM*, CH	V. long v.d. belt, black spot at f. end. Lesser streak runs parallel on S. side
September		
4	IM*	Ditto

Site Q1 *(Figures 22–24)*

July

20.8	JR, JL, et al.	First rising: southerly, quite faint dark patch
21.8–23.8	FB, CH, JR, DG	Small round black spot (like moon shadow), with faint smudge to p. side. (Other observers just saw round black spot.)
25.1–25.5	DP*, DT, DB, IM*	Small black spot in E–W streak
26.8–27.2	LT*, RM	Small round black spot
27.6–28.8	IM*, DS*	Tiny elongated v.d.s. in diffuse E–W streak. (Visual observers just saw small v.d.s.)
28.0, 30.0	DP*, DB	V.d.streak, sl. elongated E–W.
August		
1, 4	DB, IM*	Small v.d. E–W streak
6, 9	IM*, JR	Small v.d.s. (IM*, Aug.6: diffuse to Sp.)
11, 16	CH	Small v.d.s. with bright spot Sf. it
16	IM*	Small d.s. in diffuse impact belt
13–19	KM, JR, CH	Only a weak condens'n in faint impact belt, but darker when near limb
23, 26	DB*, H–JM	Dark condens'n in impact belt
28	IM*	Small condens'n in impact belt
September		
4	IM*	Barely perceptible condens'n in impact belt.

Extra spot p. site H *(Figures 22, 24)*

(A detached grey spot on Sp. side of H, at 54°S, derived from the original ejecta arc. This Sp. ejecta cloud of H had not been resolved visually, but it no doubt produced the southerly aspect of H on first rising, and it was evident in Miyazaki's image of July 20 and in a NASA–IRTF image at 2.1 μm on July 21. A HST image of July 22/23 shows it clearly as a thin diffuse grey-brown cloud Sp. site H, and this was the 'extra spot' subsequently seen from Earth. This cloud remained isolated as local winds diverted the black core material of site H to the north. It prograded rapidly, perhaps influenced by the prograding jetstream at 53.4°S although not obviously sheared by it.

Dud impacts B and N occurred at about this longitude, 29° p. impact H, but the 'pinprick' dark spots attributed to B (tentatively) and to N in HST UV images were not visible from Earth, and were separate from the diffuse cloud Sp. site H.)

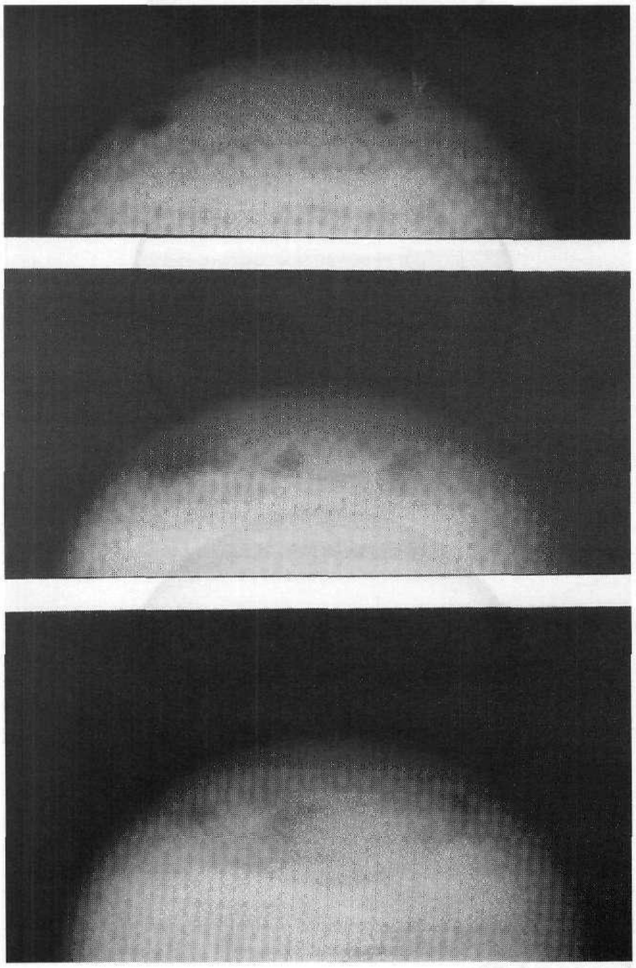

Figure 22. Early evolution sequence of site H: Isao Miyazaki (Okinawa, Japan). CCD images with a 400mm reflector.
July 20: 13.24 UT, ω_2 4. Site H has the classic structure of Sp. cloud and black core but they are only tenuously connected. (GRS on f. side).
July 23: 10.48 UT, ω_2 0. Site H split into Sp. cloud and north-streaming dark core.
July 25: 13.24 UT, ω_2 35. Site H still northerly but more diffuse.

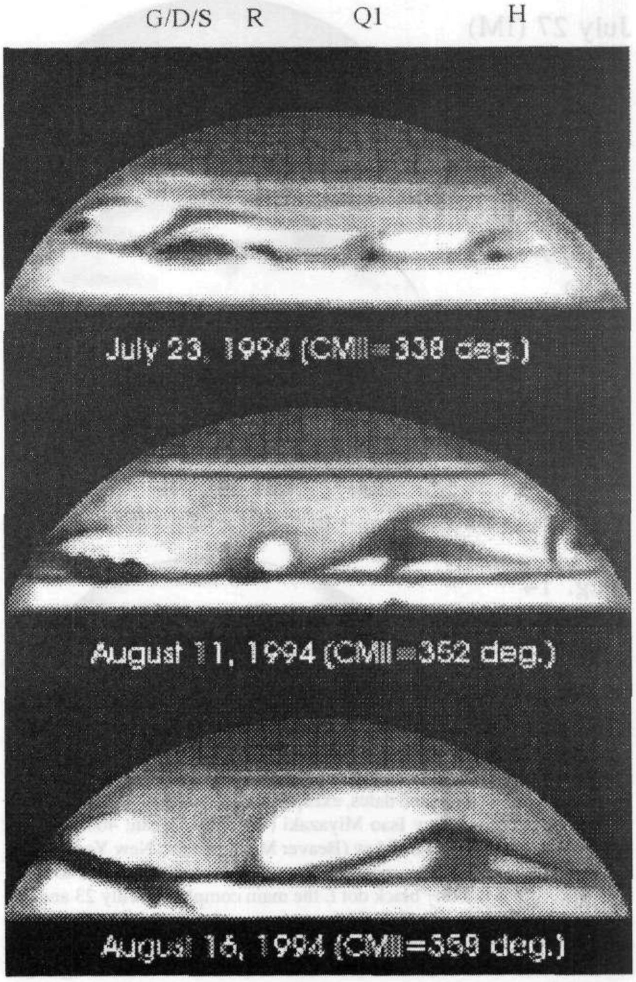

Figure 23. Evolution sequence of sites G to H: Carlos Hernandez (Florida). July 22/23 (410mm refl.): G/D/S, R, Q1, H.
Aug. 10/11 (200mm refl.): G/D/S/R towards p. limb, like an 'alien centipede' with black body. Q1 still dark with 'very bright oval' Sf. it. H follows it, now diffuse and southerly.
Aug. 15/16 (410mm refl.): continuous impact belt through G/D/S/R, Q1, H with bright large ovals to south. (However the shape of H was rather different in a Miyazaki image on the same date.)

July		
21.8	FB, H–JM	Small spot Sp. H
23.8–28.8	JR, JL, IM*, FB, LT*, TP*, LM	Diffuse, grey, southerly.
August		
4	IM*	3 small grey spots aligned N–S.
9	JR	Absent
16	IM*	Now a larger d.s., southerly, embedded in new impact belt; may be a new feature.

Site H (Figures 22–24)

(§ Indicates Sp. ejecta detached as a separate grey spot, described above.)

July		
18.8	many	First rising: large d.s., slightly S of site G
18.9	CH	First passage: v.d. core with fan to S.
20.1, 20.5	RS, IM*	Black core (like moon shadow) with wisp curving to Sp.
21.5–22.2	IM*, RM	Black core, fuzz to Sp., and small streak to Np. (Other observers saw only v.d.s.)
23.1–23.8	DP*, DT, IM*, JR	Tiny black core now has a strong v.d.streak to Np; DP* (and HST*) shows this contacts tiny w.oval at 41°S. §
25.5, 26.8	IM*, LT*	Fainter and diffuse, large dark northerly smear. §
28.8	JR, LM, DS*, SMoore	D.s. with smear to N. §
30.1	DT	V.d.s. in E–W streak. §
August		
1	PD	Large dusky diffuse haze
4	DB, IM*	Round v.d.s., but ragged edges in IM*

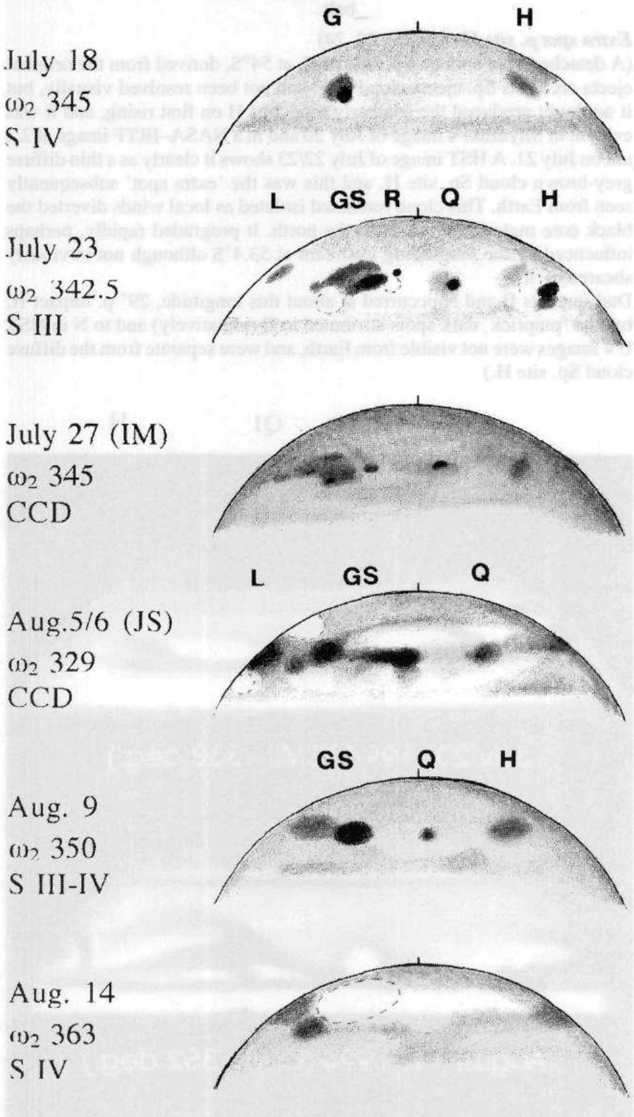

Figure 24. Evolution sequence of sites G to H: John Rogers (Cambridge, England) and others. All drawings were by Rogers using the 310mm refractor at the Institute of Astronomy, Cambridge, England, around 19–21h UT on the indicated dates, except for two views copied by JR from CCD images: July 27, by Isao Miyazaki (Okinawa, Japan; 400mm telescope); Aug. 5/6, by Joel Stuckey (Beaver Meadow Obs. New York, USA; 320mm telescope; unsharp-masked). This sequence shows site G to H.

G/D/S/R: Site R is a tiny black dot f. the main complex on July 23 and 27, not resolved thereafter. On July 23 the main complex already has two major components, one S/p. (derived from the ejecta blankets), one N/f. (the black cores); these components persist and separate thereafter. Large light area S/f. it on Aug. 14.

Q1: Appeared on July 20; black core and Sf. ejecta cloud seen on July 23; gradually becomes less prominent, and by Aug. 14 it is only a slight condensation on the impact belt.

H: On July 18, drawn 1.5 hours after impact, as a southerly dark streak. By July 23, the Sp. ejecta cloud is detached as a grey patch, while a prominent black core has developed, streaming to the N. In August it becomes more diffuse and southerly again. By Aug. 14 it is only a slight condensation on the impact belt.

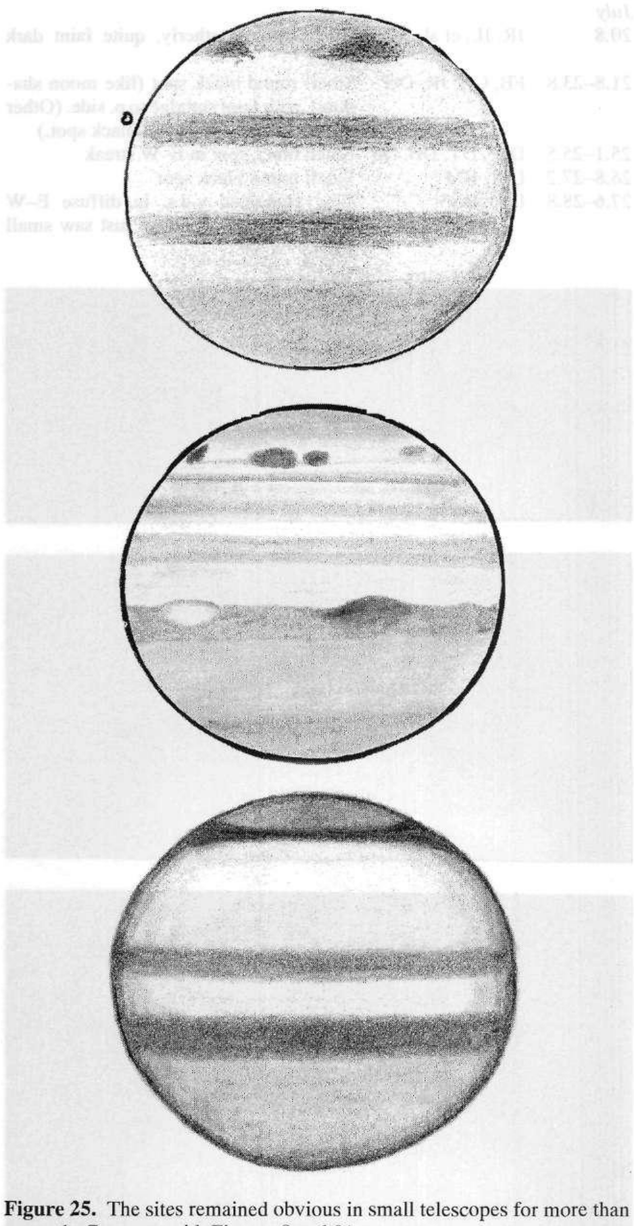

Figure 25. The sites remained obvious in small telescopes for more than a month. Compare with Figures 8 and 21.

From top to bottom:

Aug. 8: 20.45 UT, ω_2 274; 80mm OG. Complexes L and G. Io approaching occultation at left. *D. Storey*

Aug. 21: 18.33 UT, ω_2 313; 100mm OG. Complexes L (on p. limb), G (dark and double, near CM) and Q1 (faint and diffuse, near f. limb). *F. Ventura*

Sep. 2: 19.25 UT, ω_2 347; 63mm OG. Impression of a very dark impact belt mainly due to complex G. *E. T. H. Teague*

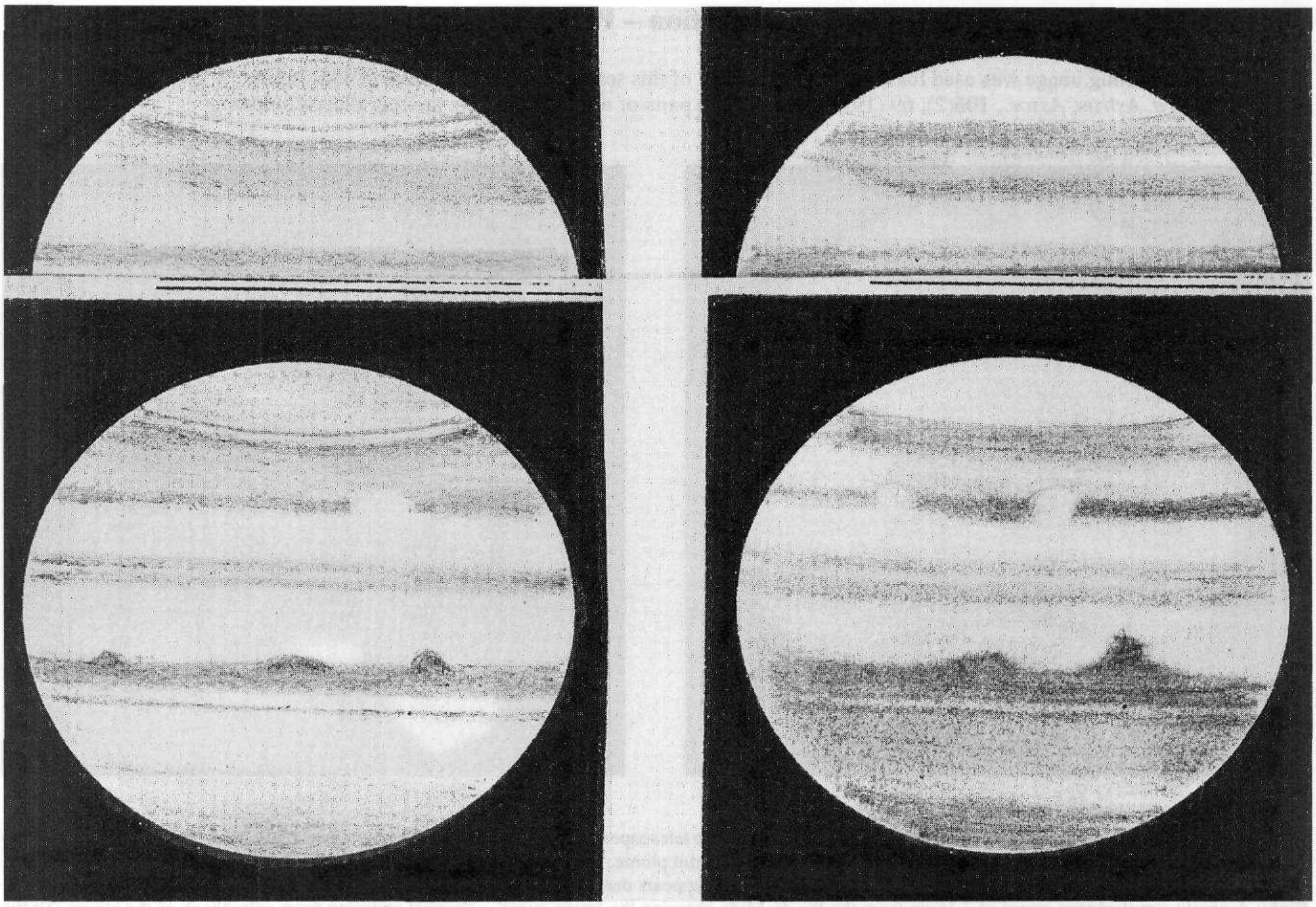

Figure 26. The impact belt at the end of the apparition, viewed from India. The apparent curvature of the belt could be due to its enhanced limb darkening. Near-simultaneous drawings by P. Devadas (left) and K. Murugesh (right).
Top: Oct. 18, 12.40 & 13.00 UT, ω_2 163 & 175.
Bottom: Oct. 20, 12.35 & 12.45 UT, ω_2 100 & 106.

7	JR	Quite conspic., prob. still small v.d.s.
9, 11	JR, CH	Less dark; a large diffuse southerly patch
13, 14	PD, KM, IM*	Dark E–W streak
14–19	JR, CH, IM*	Diffuse, southerly streak or condens'n in continuous impact belt
23, 24	DB, JL	Faint condens'n on impact belt
26	IM*	Still a long dark narrow E–W streak
September		
2	CH	V.d. streak at limb.
Site E (Figures 13, 14)		
(Dud impacts F, T, V also occurred in this vicinity but left no marks.)		
July		
17.7	KM, PD	First rising: Dark spot
17.8–18.2	many	Small v.d. or black spot (like moon shadow). A few observers drew surrounding ring or adjacent slight fuzz (also in IM*, July 21.5)
18.6–25.5	many	Small v.d. or black spot (like moon shadow); no extensions
26.1, 26.5, 31.5	DP*, IM*	Ditto but faint grey streak f. it connecting to site A
26.0–31.8	DB, DT, JR, CH	Small black spot (like moon shadow), adjacent to SSTB dusky streak on Np. side
August		
2	IM*	Small black spot with small smears to Sp. & f.
4–7	DB, JR, RS	Small d.s.
7	JR, IM*	Short dark diffuse E–W streak
12, 13	KM, PD, IM*	V.d. streak near limb
14	IM*	V.d. streak. (*Still no impact belt here*)
19	JR	Dusky streak on impact belt (alongside SSTB dark streak)
26, 31	IM*, CH	Long dark E–W streak on impact belt.

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Note: A version of Table 3 in System III longitudes is available on request from the author.

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The comet collision with Jupiter: III. The largest impact complex at high resolution

John H. Rogers, Isao Miyazaki & Sanjay S. Limaye

A report of the Jupiter Section (Director: John H. Rogers)

Comet fragments D, G, R, and S all impacted on Jupiter within an 18° range of longitude, and produced a single great dark complex. Using high-resolution maps derived from Hubble Space Telescope and ground-based images, we compile a continuous record of this complex. Many dark spots and streamers developed within it. They did not follow the normal east-west wind pattern, but showed evidence for both prograding and anticyclonic motions. There was also evidence that a nearby cyclonic white oval 'erupted' within two days after impact G.

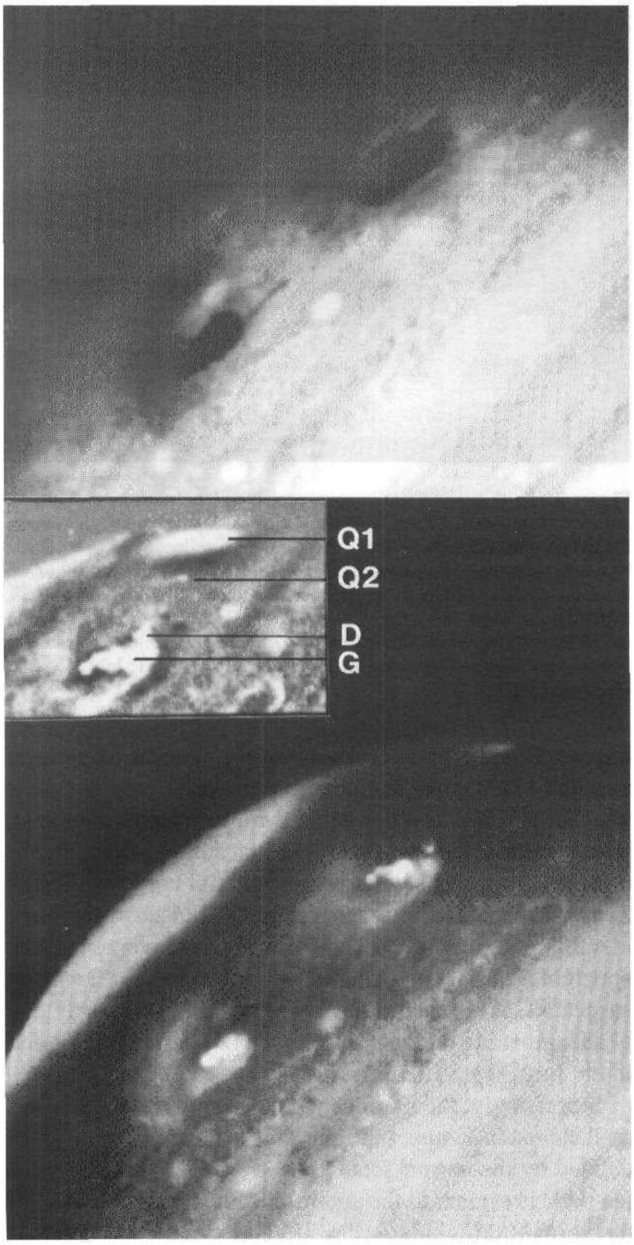

Figure 1 *(left).* Images from HST on 1994 July 20.9, showing sites L (left) and G/D (centre), just after the Q impacts. From the G impact site, strings of impact smoke are wriggling to south-preceding and north-following directions.
Top: visible light. *Bottom:* 0.89μm methane absorption band (bright features are at high altitude).
Inset: enhanced-contrast print of the limb region showing sites Q2 and Q1 at their first appearance (the dark 'shadows' are artefacts). *HST team led by H. Hammel (MIT); NASA.*

Introduction

This paper completes the BAA's report on the collision of Comet Shoemaker–Levy 9 with Jupiter in 1994. Paper I[1] reviewed what has been learnt about the impacts themselves, and Paper II[2] described the visible impact 'scars'. This paper reports more details of the largest 'scar', made by fragments D, G, R, and S.

Some of the perplexing structure in this complex was shown in images from the Hubble Space Telescope (HST)[3,4] and in CCD images by IM.[2,5] We have combined these data to give a continuous record of this remarkable complex, with high-resolution cylindrical-projection maps every 2–3 days.

The data are shown in Figures 1–3. The maps are aligned in System III for consistency with the HST data, but are all shown with south up. All latitudes are zenographic. As the fine details of the black cores cannot be reproduced well, we also show interpretative sketches of the maps, in Figure 4.

The nominal positions of the impacts are shown in Figure 4a. The longitudes are from the accepted impact times (see Table 1 of Paper II). The latitudes are from the predictions by P. Chodas and D. Yeomans:[4] impacts D and G were at 47.4°S and 47.5°S respectively, whereas impacts Q2, R, and S were at 48.0–48.2°S. The impacts were thus in the SSS Temperate domain, which is bordered by prograding jetstreams at 53.4°S to 43.6°S, and divided by a modest retrograding jetstream at 49.4°S, as marked on Figure 2 and Figure 4a. These jetstreams were discovered in 1979 by

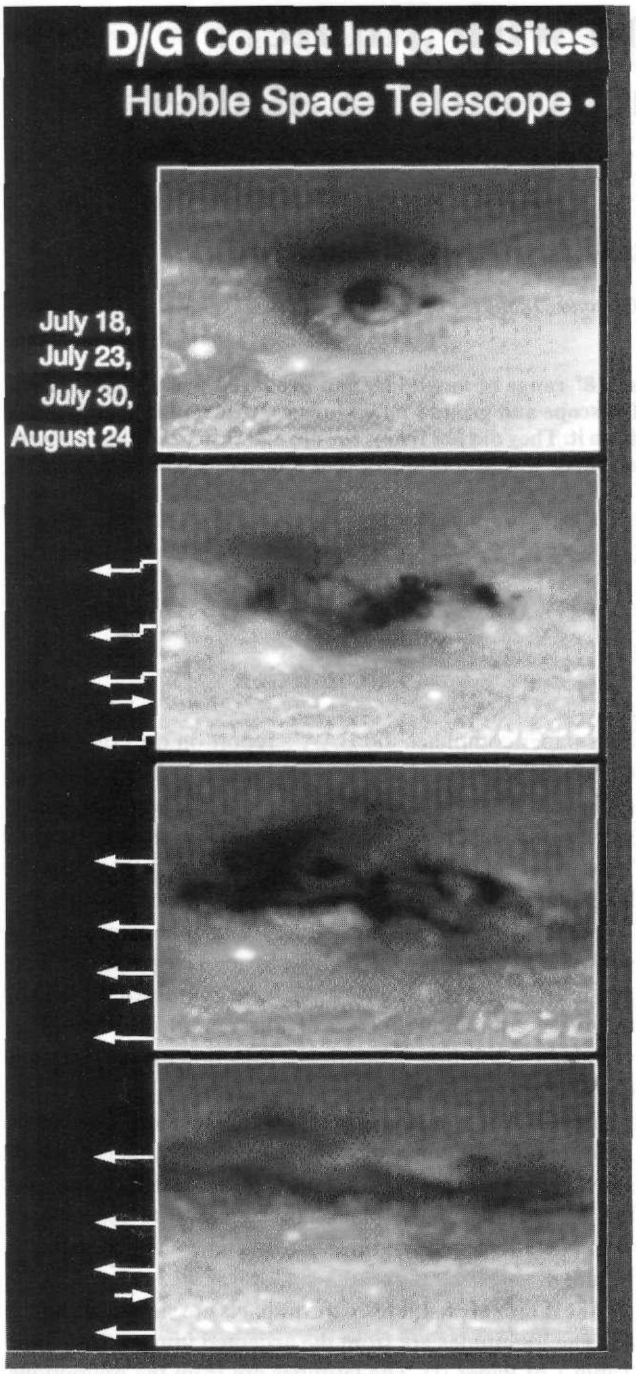

Figure 2. Images from HST in the near-ultraviolet, 336nm, projected onto maps centred at λ_3 = 28, zenographic latitude = 46°S. (In System II, the centre is λ_2 = 317 (July 18) to λ_2 = 314 (July 30).) The maps span λ_3 = 358–58 and latitudes 26–66°S. South is up. Arrows at left indicate the prograding jets revealed by *Voyager* at 53.4°S, 43.6°S, 36.5°S, and ~28°S. From top to bottom, the dates are: July 18 (less than 2 hr after impact G); July 23; July 30; August 24. *HST team led by H. Hammel (MIT); NASA.*

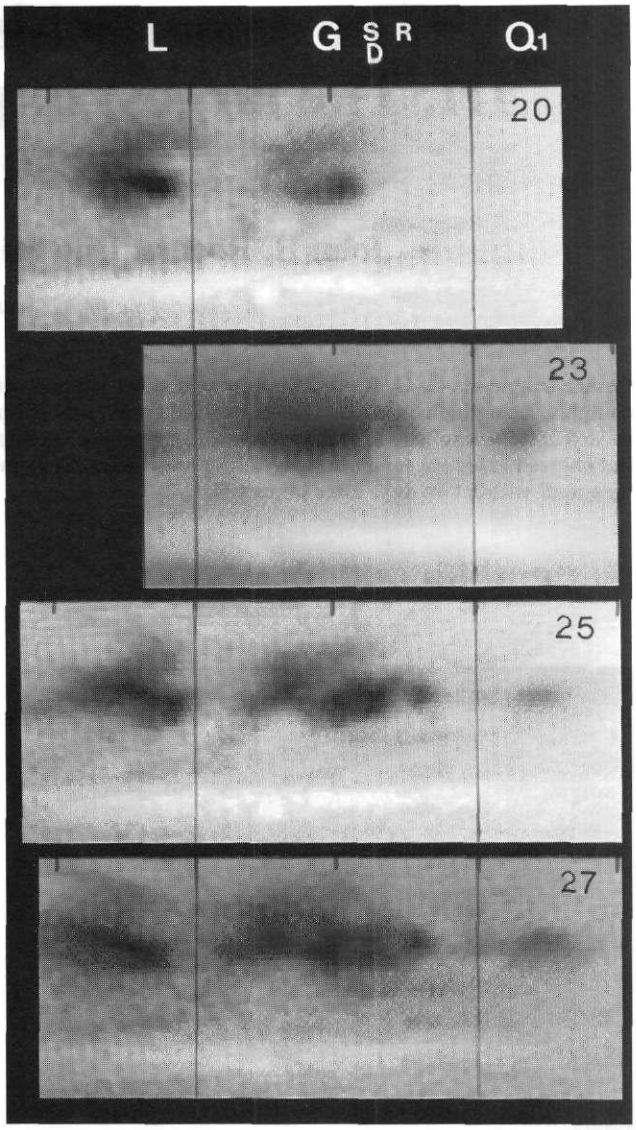

Figure 3. Earth-based CCD images, projected into maps by S. Limaye. All are by I. Miyazaki (40cm reflector, Okinawa, Japan; white light) except for the second which is by D. C. Parker (41cm reflector, Florida, USA; blue light; positions approximate). Parker took other images, in colour, on the same dates as Miyazaki's.[6] The vertical lines mark λ_3 = 358 and 58, matching the edges of Figure 2. South is up. Each map extends down to the SEB; note the white STropZ oval at λ_3 = 13 (λ_2 = 300). From top to bottom, the dates are: July 20, 11.40 UT; July 23, 00.19 UT; July 25, 11.06 UT; July 27, 12.50 UT.

Voyager[7] and were essentially the same in 1994 according to HST images.[8]

Appearance and drift of the dark material

The images of July 18 and 20 showed sites D and G only. By July 20 (Figure 1), the core of site G was emitting black blobs in both the south-preceding and north-following directions. This was more evident on July 23. By July 23, impacts R and S had occurred, and they can be recognised as small black cores in the correct latitude. It is not clear whether site D was still visible then, or whether the black spot at that position was new material spilling from sites G or S. As black blobs emerged, the central cores of sites G, S, and R appeared to wander slightly, but they remained identifiable up to July 30 without much movement. (The apparent retrograding of core G reported in Paper II was, as suspected, partly due to the later impact S, and partly due to a lengthening dark band along the northern flank as seen in the July 30 HST map.)

Surprisingly, the motions in and around the black cores as sketched in Figure 4 did not follow the expected pattern defined by the normal jetstreams. Cores G, S, and R emitted dark streamers to the south-preceding side, contrary to the normal retrograding flow at that latitude. We interpret these as rising smoke plumes which entered the same prograding stratospheric current that was revealed by many of the diffuse ejecta clouds (Paper II). They are also consistent with anticyclonic motion. Also, core G emitted a dark blob to the north, which eventually merged with other dark spots to form a sinuous band at ~44°S whose f. end was slightly retrograding (July 30), contrary to the normal prograding flow there. This suggests that smoke from site G was entrained in anticyclonic flow around the rising smoke column, as sketched in Figure 4b.

This evidence for anticyclonic flow supports predictions that the hot impact sites could form anticyclonic circulations, analogous to Jupiter's well-known white ovals. The form of the sinuous band in the HST July 30 image suggests that it curved around cores S and R as well as G. Reta Beebe[8] has noted anticyclonic motion around the cores of site L and possibly Q1 in HST images, but smaller sites showed idiosyncratic motions.[2,4,8] Therefore the evidence from these images (essentially, the retrograding suggested by the HST images of July 20 and 30) must be interpreted with caution. In any case, the circulation may have been restricted to the stratosphere, and no long-lived ovals were formed.

The ejecta crescent of site G was initially more diffuse, and the irregular p. end of the whole complex prograded rapidly (Paper II). However this part also broke up into several patches and streamers. Surprisingly, a very dark patch is visible in all maps from July 23.0 onwards which stayed 12–18° p. site G. It was at 48°S and was probably a condensation of ejecta arc material in S^{3}TB latitudes. In parallel, much of the ejecta arc evolved into a diffuse band around 55°S, in S^{4}TB latitudes. So this stratospheric material may have become concentrated over regions that are cyclonic in the troposphere. The maps of July 27 and 30 also show a streamer extending even further south, to >60°S.

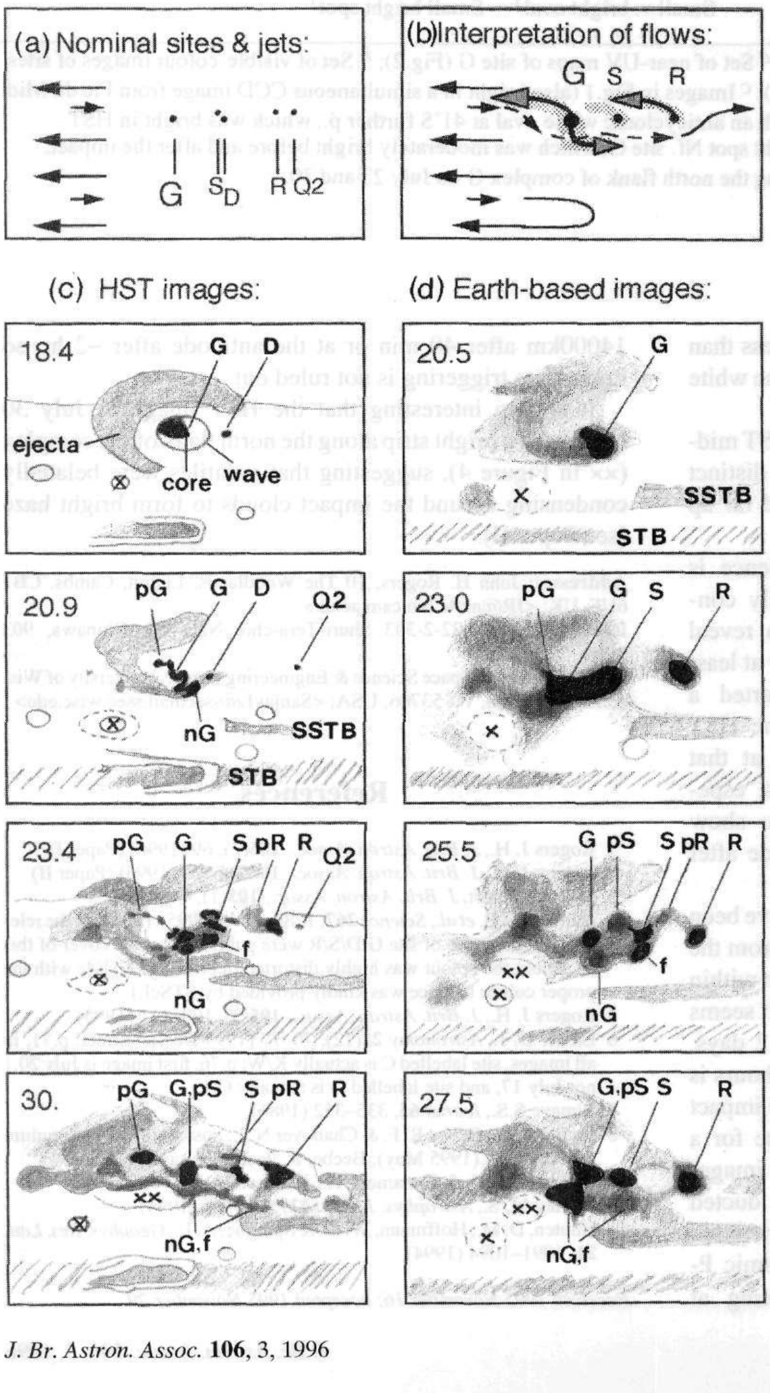

Figure 4. Interpretative diagrams of the maps (by *JHR*), labelled by decimal date. Each panel covers the same area as in Figure 2.

(a) Nominal sites and jets (see text). Impact positions are from refs. 2 and 4. At left are the latitudes of the normal jovian jetstreams.[7]

(b) Interpretation of flows (see text).

(c) HST images (Figure 2). Note that a rough sketch from the images of July 20.9 (Figure 1) has been inserted. Because the *HST near-UV prints are black in the core region, detail in the* densest parts has been supplied from HST's global visible-colour maps.[4,5]

(d) Earth-based images (Figure 3).

Features are labelled as follows:

G, D, S, R: black spots coincident with impact sites.

pG, pS, pR: dark material streaming in the south-preceding direction from the impact sites (possibly rising into a prograding stratospheric current).

nG: *dark material spilling north from site G, later retrograding with 'f'* (possibly showing anticyclonic flow around the rising smoke column).

f: a black spot at the site of D, but it may rather have emerged north from site S or north-and-retrograding from site G.

×: cyclonic white spot which 'erupted'.

××: bright strip along north flank of the complex in late July.

A cyclonic white spot 'erupting' after impact G

A bright spot north-preceding site G (× in Figure 4) was of interest because it apparently brightened soon after the impact, possibly erupting into the stratosphere. From its latitude of 39°S it must have been a cyclonic spot in the SSTB domain. The data are summarised in Table 1; they include not only the images used in Figures 1–3, but also other images by IM (some of which showed it more clearly), visual drawings by JHR (Paper II), and publicly-released images by HST at other wavelengths.

In our visible-light data, the spot brightened between July 18 and 23, and it was especially bright when near the limb, suggesting high altitude. In HST images, both visible and near-UV, the spot always had a bright core but it developed

Table 1. The cyclonic white spot near impact site G.

July	*Miyazaki images*	*Rogers drawings*	*HST near-UV maps* [a]	*HST colour images* [b]	*HST methane images*
18	(G first passage) Not bright	(G second passage) Not bright*	(G first rising) Small, v. bright*	(G first rising) Mottled, inconspicuous, but v.small v.bright core*	(G first rising) Not visible
20	Quite bright spot	(During Q impacts) Not bright*	–	(Just after Q impacts)[c] Small bright core with diffuse light halo	(Just after Q)[c] Only a small faint light core
23	–	Bright spot, –> brilliant, almost irradiating at p. limb.	Small v. bright core, diffuse	Small bright core with diffuse light halo	–
25	Quite bright spot	Bright spot			
27	Light spot†	–			–
30	–	Quite bright	Small v. bright oval†	Small bright spot†	–

HST data are from publicly released images, especially: [a] Set of near-UV maps of site G (Fig.2); [b] Set of visible-colour images of sites L + G[4]; also a set of global maps at lower resolution[4,5]); [c] Images in Fig.1 (also bright in a simultaneous CCD image from Pic du Midi).
* This white spot Np. site G should not be confused with an anticyclonic white oval at 41°S further p., which was bright in HST images especially July 18; nor with another cyclonic light spot Nf. site G, which was moderately bright before and after the impact.
† This white spot was north of a separate light haze along the north flank of complex G on July 27 and 30.

a diffuse halo after July 18. (The first image was less than 2hr after the G impact so we do not know whether the white core appeared during that interval.)

Most strikingly, in the single publicly-released HST mid-UV image (255nm), on July 21, this was the only distinct bright spot on the disk – implying that it extended far up into the stratosphere.

Was this spot's behaviour unique? The evidence is inconclusive at present. Visual observations rarely concentrate enough on the SS Temperate region to reveal such events. *Voyager* visible-light images did show at least one similar bright spot eruption which converted a SSTB cyclonic oval to a filamentary region. The HST mid-UV image is the only one ever published at that wavelength. Further study of more HST images, especially in the methane band, will be needed to show whether this cloud actually erupted to high altitude after impact G.

Is it plausible that the spot's brightening could have been triggered by the G impact? Possibly a shock wave from the impact induced precipitation, updraft, and expansion within this cyclonic spot, as in a terrestrial thunderstorm. It seems reasonable that this could have happened within 2 days. Whether it could have happened within the first 2 hours is more doubtful, as the spot was 14000km from the G impact point. In those 2 hours, the only visible candidate for a tropospheric wave (the sharp ring in the July 18.9 image) had only travelled 3500km,[4,9] while sound waves ducted along the tropopause (sonic boom) could have travelled 5500km. However, descending sound waves (seismic P-waves) could have travelled faster,[10,11] resurfacing at 14000km after 40 min or at the antipode after ~2 hr, so immediate triggering is not ruled out.

It is also interesting that the HST image of July 30 confirmed a bright strip along the north flank of the complex (xx in Figure 4), suggesting that volatiles were belatedly condensing around the impact clouds to form bright haze (see Paper II).

Addresses: John H. Rogers, 10 The Woodlands, Linton, Cambs. CB1 6UF, UK; <JR@mole.bio.cam.ac.uk>
Isao Miyazaki, 2-22-2-303 Shuri-Tera-cho, Naha-shi, Okinawa, 903 Japan.
Sanjay S. Limaye, Space Science & Engineering Center, University of Wisconsin, Madison, WI 53706, USA; <SanjayL@ssecmail.ssec.wisc.edu>

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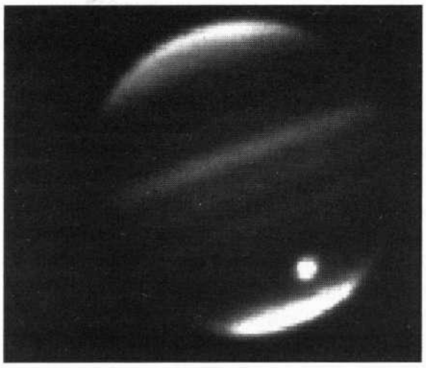
Notes and News

The Great Comet Crash: the view gets clearer

In 1996 July, a conference at the Meudon Observatory, Paris, reconsidered the 1994 collision of Comet Shoemaker–Levy 9 with Jupiter. There were no major revisions of conclusions reached a year earlier (Rogers J. H., *J. Brit. Astron. Assoc.,* **106**(2), 69–81 (1996)) but some outstanding questions have been clarified, so this account will be presented as an updating of topics raised in that review.



July 1994: an infrared image of Jupiter shows the effect of the impact of SL–9 fragment A. John Spencer (Lowell Observatory) and Darren Depoy (Ohio State University) used the 4-meter telescope at the Cerro Tololo Interamerican Observatory (CTIO) at La Serena, Chile.

Structure and size of the comet

Were the 20 'fragments' solid planetesimals, or re-aggregated rubble-piles? W. Benz and E. Asphaug have now ruled out the former option; after an SL9-type tidal breakup, the fragments must reaggregate into clumps by self-gravity. But these clumps could contain large solid lumps, so a compromise solution is possible. Only Z. Sekanina now holds out for a large, solid, initial object – 9km across, breaking up 2.5 hr after perijove – but as a tidally-stretched rubble-pile would be ~9km long at that time, it can satisfy the observations just as well.

More difficult is the question of secondary splitting, which does seem to require coherent and heterogeneous objects in the clumps, and may well have involved cometary activity. Sekanina, with P. Chodas and D. Yeomans, presented a complete genealogy of the fragments, in which all the off-line ones (which later disappeared or fizzled) split off from the next-following on-line fragment, some time in 1992 (or 1993 April for Q2). They proposed that these 'wimps' were small fragments flung off the rotating larger fragments during local afternoon, by centrifugal force after warming by sunlight; their motion can be explained if all the fragments retained similar rotation axes. In a mixed rubble-pile model, perhaps the same could be achieved by interactions of low-mass, mixed-density rubble orbiting or jostling around a large rotating lump.

There is now good agreement between most estimates of the sizes and energies of the fragments, although Sekanina still argues for larger sizes. The rubble-pile model predicts a progenitor with density 0.5g/cm^3 and diameter 1.5km (with a two-fold uncertainty because of its possible rotation). In that case the largest fragments (G, H, K, L) would have approximately density 0.5g/cm^3, diameter 0.75km, mass 1×10^{14}g, and impact energy 2×10^{27} erg. Indeed, all the best estimates of the sizes of the impacts are now converging within a factor of two of these values (see Table).

Effects on the magnetosphere and ionosphere

The X-ray emission recorded by ROSAT during the K and P2 impacts was an intensification in the normal northern auroral region. This may have been caused by the cometary coma dust burning up in the ionosphere, triggering magnetic waves which spread to the opposite hemisphere.

Infrared emission from H_3^+ and methane in the ionosphere revealed the earliest stages of an impact, as recorded by S. Miller's group at UKIRT during impact C. They found the ionosphere beginning to heat up 4 minutes before the impact, presumably due to the coma meteor storm. Within minutes after the impact, the temperature reached several thousand degrees, and faint hot methane lines were blueshifted by 25km/s – probably the initial blast wave surging over the limb and out into space. Then the main part of the plume came crashing down to dazzle the detectors in the 'main event'.

Dynamics of the impacts

The *Galileo* team have now worked out a temperature of ~24,000K for the bolide entry flash seen in impact Q1! For impact G, their value of 8800K probably refers to 1–2 seconds later, as the entry trail began to erupt into the fireball.

Of the two groups leading the modelling effort, the one which previously favoured large impactors (D. Crawford & M. Boslough) presented a new model which favours smaller ones, agreeing with others (see Table). The mechanism of their plume is still somewhat different, and they argue that the impactors must have penetrated at least 30km below the ammonia clouds.

It remains certain that the impacts did penetrate into the troposphere, as expected for impacts of this size. The evidence is: (i) the level of the initial fireball viewed by *Galileo*; (ii) models for production of 3000km-high plumes; (iii) the presence of sulphur separate from the cometary water; (iv) the vertical distribution of smoke in the cores of the sites; (v) the presence of ammonia lofted into the lower stratosphere.

Thermal effects

A new theme at this meeting was the importance of *dust or smoke in the distribution of the heat.* These particles were responsible for the huge thermal emission seen in the splashback. During this main event, the 'dust' remained at 600K (±100K) throughout (P. Nicholson), but the gas temperatures of methane and CO climbed steadily from ~600K to 4000–5000K (K. Zahnle, R. Knacke). The reason is that dust radiates heat away more efficiently.

The dust in the ejecta was confirmed as *being in the stratosphere:*

– an altitude of >1000km was deduced from parallax on optical images (S. Limaye);

– initially the top was around the 0.5 mbar level, from HST image photometry (R. West);

– initially the bulk of the dust was above the 30 mbar level, from 7–13μm imaging (T. Livengood et al.), settling to the 35 mbar level over the week following the impacts.

The observed heating above the impact sites was reviewed by B. Bézard, who reinterpreted various groups' data to conclude that all the observed heating was in the stratosphere, from the 0.5 mbar level upwards, the enhancement reaching 30–60° at higher levels. This implied ~3×10[26] ergs of heating above site L when 11 hours old – *more than had been radiated away* (see Table). The IRTF report of heating in the troposphere, which would require ~10[29] ergs, may be (controversially) interpreted as due to emission from warm dust in the stratosphere.

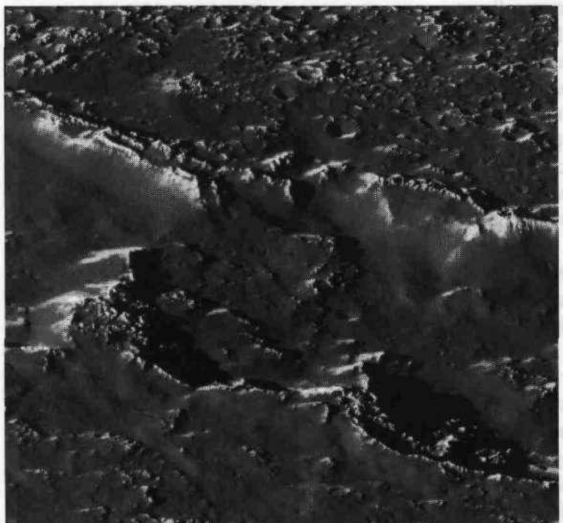
The presence of dust also explains why the stratosphere cooled rapidly – within one *week for most sites. Very fine silicate particles,* so fine that they remained suspended for weeks above the 0.1 mbar level, explain this behaviour.

Sizes of the SL9 impactors

Technique	*Authors*	*Constraint*	*Diameter (metres)*	*Mass ($x10^{13}$ g)*	*Energy ($x10^{26}$ erg)*
(a) Models of the plume					
(i) K. Zahnle & M. Mac Low		Mass	600–700 m	7	10–20
or (ii) D. Crawford & M. Boslough		Diam.	300–600 m	1–6	2–10
(b) Energy measured in plume:					
Initial fireball emission (GLL)	T. Martin	Energy			0.08
Splashback emission (EIR)*	G. Orton	Energy			0.1–0.3
Heating of stratosphere*	B. Bézard	Energy			~2
Heating of troposphere	G. Orton	Energy			≤1000?
* (from plume kinetic energy)					
TOTAL			>350 m	>1	>2
(c) Debris observed:					
Smoke (carbon, etc?)	R. West, etc.	Diam.		~1–10	
Silicates	R. Knacke	Mass		~1	
Water	G. Bjoraker	Mass		0.3–1.0	
CO	R. Knacke	Mass		~15	
TOTAL			~1300 m	~20	~35

This Table gives the latest estimates of the sizes of SL9 fragments G and K. In terms of mass and energy, fragment L was almost twice as large; H about half as large; A, E, Q1, S, T, W, about one-third as large; and C and D smaller still. This makes the total comet mass about 6–7 times the fragment masses listed here. Columns list: the authors or speakers at Paris who presented these results; the parameter which was determined; and the derived diameter, mass, and energy, assuming a sphere of density 0.5 g/cm³. (10^{26} erg = 10^{19} J.)

Galileo's update on Comet Shoemaker–Levy 9: comets are rubble-piles



This is perhaps the most scientifically important image to come from the *Galileo* orbiter mission, as the imaging team targeted it in order to answer a key question about the origin of the solar system. It is believed that the solar system formed by condensation and accretion of dust and ice from a gas cloud, and comets are the leftovers. But are pristine comets made of one or a few fairly large nuclei (planetesimals), or are they 'rubble-piles' of many smaller pieces? This question has been controversial ever since Comet Shoemaker–Levy 9 was pulled apart by Jupiter's tidal forces into approximately 20 fragments, which went on to impact the planet. Although most of the fragments behaved like solid nuclei, it was shown that they could equally well be explained as rubble-piles which would have reaggregated by self-gravity very soon after the comet was split.

For more information, scientists turned to Jupiter's satellite Callisto, which is marked by at least eight chains of craters. These were clearly formed by objects like Comet Shoemaker–Levy 9, which happened to hit Callisto just after they had been disrupted by passing close to Jupiter; their frequency suggests that they come from typical comets. If the fragments were solid nuclei, each crater in the chain should have a classic bowl or central-peaked shape; but if the fragments were rubble-piles, they would not yet have fully reaggregated by the time they got out to Callisto, and they would produce craters with irregular floors.

This is the first close-up image of such a crater-chain, and it clearly shows irregular floors. The image was taken during the *Galileo* C3 encounter on 1996 November 4, from a range of only 1567km, and covers an area about 13km across. It shows three overlapping craters within a crater-chain at 35°N, 46°W (in the rings of Valhalla). At least two of them have very hummocky floors, so if these are typical, comets are rubble-piles. Another interesting aspect of the image is the smooth coating over much of Callisto's surface, like a thick layer of dust or snow of unknown origin, which seems to have buried smaller craters. The bright slopes visible in this picture appear to be fresh ice on the steepest and most north-facing slopes, perhaps where downslope movement has kept the underlying ice exposed. *(NASA image P-48127.)*

John H. Rogers

Chemistry and long-term evolution
The *Galileo* Probe data have produced confusion rather than clarification, but probably make little difference to the conclusions. If the atmosphere is indeed devoid of water, K. Zahnle showed that most of the correct molecules can still be produced if the cometary material comprised 6–8 percent of the mass of the plume. But anyway, it is clear both from the sulphur in the plumes and from the energies of the impacts that the impactors did not go deep enough to encounter jovian water. In any case, S. K. Atreya argued that the *Galileo* results were probably due to a strong local downdraught of dried-out air in the NEBs hotspot where the Probe entered, and that the comet impact sites might have had a composition much closer to what was expected.

Cometary water was deposited high in the stratosphere, and might have been dense enough to condense into a white haze (J. Moses). So might the ammonia which welled up into the lower stratosphere. So it is interesting that HST visible-light images in late July, and mid-ultraviolet images in late August 1994 possibly showed bright clouds along the edges of the dark impact material – although these remain to be analysed.

CO, CS and HCN have all remained in the stratosphere up to mid-1996, at levels of 0.02–0.4 mbar and 155K, showing little if any diminution and spreading close to the equator (A. Marten). They may last as long as 30 years, which is the theoretical time for diffusion from the stratosphere into the troposphere. However, this still seems too short for cometary impacts to be a major source of the normal jovian CO.

Amateur images showed that the visible dark belt broke up and became unrecognisable after 1995 July (J. Rogers & M. Foulkes). But dark debris was visible for longer in HST mid-UV images (R. West); as shown by the sole image at 255nm previously published, during impact week, this wavelength is exquisitely sensitive to absorption at any level in the stratosphere. Such images in 1994 August showed a spectacular broad convoluted impact belt. Images in 1995 and 1996 April showed a thinner, diffuse impact belt mainly near the limb (spreading to ~20°S but no lower, unlike the gases; most of the dust had probably now settled to ~100 mbar), and also an incomplete belt around the pole (>70°S) – possibly related to a very dark south polar belt (63–69°S) seen in I. Miyazaki's images in 1995 and 1996.

Meanwhile, infrared images at 2.3μm also showed diffuse impact haze persisting in the south at least until 1995 September (H. Hasegawa; J. Spencer); and HST images at 0.89μm still showed slight limb-brightening at the impact latitude in 1996 April (R. West).

John Rogers, Michael Foulkes & Richard McKim, *Jupiter Section*

Mars Section

Mars 1996–97: first interim report

This is a short account of observations covering the period 1996 August 4 until November 30. During this period the disk diameter increased from 4″.2 to 6″.5. This account will show how much can be done many months before opposition.

North polar region
From the data so far to hand, the polar hood had cleared in the longitude of Syrtis Major by September 17, but NPH persisted at some other longitudes till later. This behaviour is quite normal and follows the usual seasonal pattern. David Gray showed an indentation in the cap on November 22 (Iaxartes/Chasma Boreale). No rifts were seen in the telescopic observations, the cap being in the slow regression stage.

Surface features
These closely resemble the 1995 apparition (see the *Journal* **105**(4), 157–158 (1995)). Published HST images for September 18 and October 15 (see cover) showed Propontis I (with its comma-shaped *f.* end) clearly, but the E. and SE (IAU) borders of Elysium, including Trivium Charontis–Cerberus, continue to be faint. The Atheria darkening – or secular enlargement of Morpheos Lacus – remains visible to the NW of Elysium, and that part of Mare Cimmerium visible on the images has the same contour as before.

Dust storms (yellow clouds)
HST imaged a small storm in the longitude of Propontis and at the southern edge of the NPR on September 18, one of the dates time had been reserved on the telescope for Mars imaging, perhaps on the first day of the storm. The storm had a remarkably deep orange colour. About half the cloud was visible above the cap, and half to the south. I would speculate that the event was associated with the final dispersal of the N. polar hood. Because of the limited possibility of altering the HST timetable no further images of the same region were secured until October 15, when the storm had mostly dispersed. The draft BAA Martian Yellow Cloud Catalogue (1659 to 1993) contains no similar incident. Local storms have been seen at the edge of the shrinking south polar cap by past spacecraft, but never in association with the northern one.

On 1996 November 22 David Gray (415mm Dall–Kirkham Cass.) found two clouds over Ophir and Candor respectively, the former the larger, impinging upon Aurorae Sinus. Both clouds were marginally luminous in yellow (W15) and orange (W22) filters, but rivalled the NPC in brightness in red light (W25). Dust? Gray had the same impression next day in poorer conditions. Maurice Gavin (300mm Schmidt–Cass.) took a series of CCD images on November 24; this showed Mare Acidalium, Nilokeras, Meridiani Sinus and Margaritifer Sinus well; no *large* cloud over Ophir–Candor could have escaped detection. The Director contacted the OAA and ALPO about the UK observations; further reports are awaited.

White clouds
The September and October HST images reveal seasonally early orographic clouds over the martian volcanoes, which were imaged on or near the evening terminator. Otherwise, there is nothing of special interest under this section.

HST imaging timetable
The Director understands that future images will be taken as follows:

1997 March 25–31; CML= 15, 105, 195 and 285°
1997 April 14–18; CML= 45°
1997 May 17–21; CML= 45, 165, 285°
1997 June 26–30; CML= 30, 75, 345°

Section members should try to observe at these dates and times whenever possible. Members are reminded of the necessity of prompt, fortnightly reporting of routine work, and immediate reporting of dust storm events. Keep up the good work!

Richard McKim, *Director*

Title pages, volume 106

The index to volume 106 is included in this issue of the *Journal*. A mailing list is kept of those who require title pages for binding, and these will be distributed shortly. Please write to the Editor if you would like to be added to this list and receive title pages for this and future volumes.