CCD Imaging of Jupiter During the Comet Shoemaker-Levy 9 Impact Using the Danish 1.54-m Telescope at ESO

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1. Introduction

After the discovery of the disrupted nucleus of comet Shoemaker-Levy 9, it was quickly established that the sub-nuclei would strike Jupiter in mid-July 1994. Based on hydrodynamics models [1], it was estimated that although the impact sites could not be seen directly from the Earth, the flashes from the impacts might be observed reflected from the surface of the Galilean satellites or from the thin Jovian ring. As the time of the impacts neared and more precise positions became available, it became clear that the fireball, which might reach a total luminosity of 3 10^{25} erg s^{-1}, might even be visible above the limb of the planet. The programme at the Danish 1.54-m telescope was designed to search for evidence of the impacts.

A special HiSis 22 camera, designed by a small French company managed by amateur astronomers, was mounted at the Cassegrain focus of the telescope. The detector was an anti-blooming Kodak KAF-0400L CCD with 768 $\times$ 512 pixels. The pixel size of 9 microns corresponded to 0.14 arcsec at the focus of the Danish telescope. One-third of each pixel was insensitive because of the anti-blooming gate structure. The peak quantum efficiency reached about 35 % around 750 nm. The read-out was fast: about 4 s to read the CCD frame when binned 2×2 with a read-out noise of 12 e^- at –10 C. A rapid read-out was also available for a specified window on the CCD giving near-continuous imaging. This mode was used to observe flashes at the limb of Jupiter. The camera was cooled by Peltier effect and was very simply connected to a PC via the parallel port.

When flashes were not expected, it was planned either to observe Jupiter's disk (to search for post-impact phenomena) or to observe the Io plasma torus (to search for changes produced by cometary dust entering Jupiter's magnetosphere). The latter programme proved impossible probably because the gain of the CCD was not set high enough. We also failed to obtain any useful data on Jupiter's ring. However, the observations of Jupiter's disk are of high quality and are providing good information on the development of the appearance of impact sites.

2. Available Data and Current Reduction Status

The run began on the night of July 17 (the night after the first impact). Despite poor weather conditions in the middle of the run, good data were obtained on several nights. The anti-blooming CCD system proved to be an excellent tool for the study of flashes from the impacts. A continuous data set was obtained near the time of the F impact while an attempt was made to observe the L impact in daylight (16:30 local). The F impact was not detected which appears to be consistent with other reports (e.g. from the observers on the 3.6-m using TIMMI) that this impact was unusually weak. Although some observations near the time of impact L were obtained, persistent heavy clouds eventually forced us to close a few minutes before the predicted impact time.

The main data set therefore comprises a number of high-quality images of Jupiter's disk in four wavelengths (894 nm, 829 nm, 727 nm and 751 nm). The images obtained are summarized in Table 1.

At the time of writing, data from the night of July 17–18 are reduced and calibrated. The absolute calibration of the instrument was performed by comparing the brightness of Jupiter's disk with standard star frames obtained immediately afterwards at a time when the atmosphere was clear and stable. This observation of Jupiter's disk was then used as a standard and all images were normalized to this. At present, we estimate the flux calibration to be good to around $\pm$ 15 % . The resolution was seeing limited and quite variable particularly on the first three nights.

3. Preliminary Results

3.1 General appearance of impact sites

The absorption of sunlight by methane in Jupiter's atmosphere is strong at 8900 Å giving rise to a Jovian geometric albedo of only about 5 % (see e.g. Tomasko (1976) [2]) compared with a value of 40 % in the continuum. The impact sites proved to be clearly visible as bright spots against the dark background of Jupiter at 8937 Å. This contrasted sharply with the dark appearance of the impact sites relative to Jupiter's continuum. In Table 2, we catalogue the maximum observed deviation of the brightness of site H (three hours after the impact) from Jupiter's normal brightness. It should be noted that these deviations form lower limits because of the effects of "seeing". Although the 7270 Å filter is also centred on a methane absorption, this absorption is not as deep as at 8990 Å. We also give an estimate of the reflectivity (I/F where π F is the solar flux) of the impact site at the same phase angle before the impact occurred. The error on this value is estimated to be about 20 %.

3.2 The morphology of impact sites D and H

The shapes of the impact sites were clearly asymmetric. The site of impact H is a good example of this (Fig. 1). Impact H occurred at 19:26 UT on July 18. Im-

TABLE 1. *The data set obtained with the Danish 1.54-m telescope*

Date	UT Coverage	Conditions	Image obtained
17–18/7	23:46–03:53	in patchy cloud	163
18–19/7	23:01–02:10	in occasional heavy cloud	56
19–20/7	22:10–02:16	in very poor conditions	21
20–21/7		NO DATA	
21–22/7		NO DATA	
22–23/7	21:23–22:58	in daylight	96
	02:46–03:37	good data	54
23–24/7	23:067–03:35	quality data 0.7" seeing	249

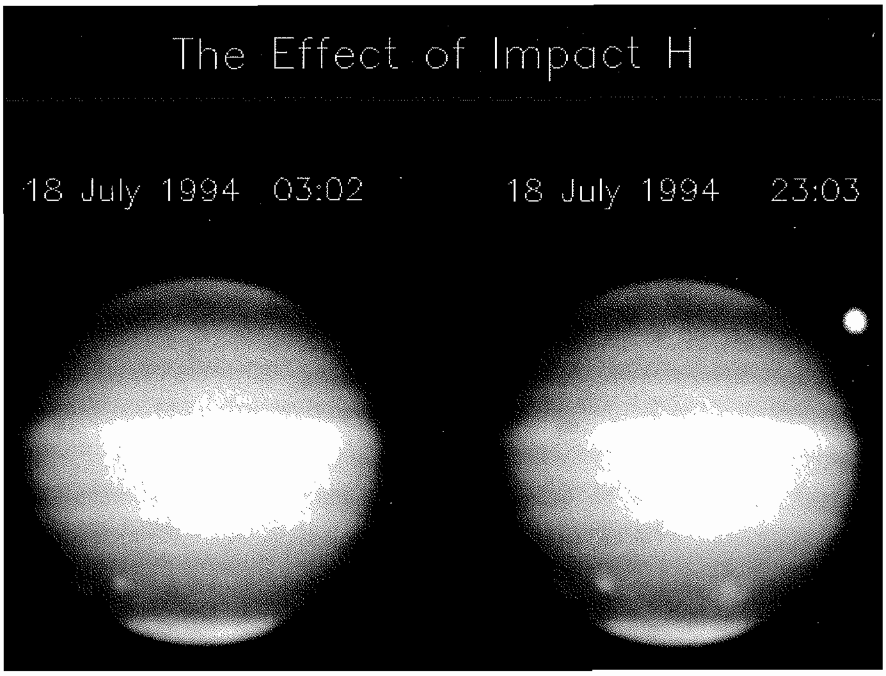

Figure 1: *Impact H occurred at 19:26 UT on July 18, 1994 during daylight at La Silla. An image taken the previous night shows the sites of E and A. The large white spot is actually the Great Red Spot. North is up, celestial east (the dawn terminator) is to the left. Twenty hours later, after 2 Jovian rotations, the effect of impact H can be seen (lower right). It appears to be asymmetric with a diffuse arc-shaped structure to the south-west. The bright spot in the upper right corner is Ganymede.*

TABLE 2. *The maximum change in brightness near site H three hours after impact*

Filter Å	Bandwidth	Description	Reflectivity of site before impact	Change in brightness (%)
8937	43	methane	0.035	53
7271	19	methane	0.217	–11
8290	46	continuum	0.550	–12
7508	47	continuum	0.417	–20

ages of the impact site were first obtained at 23:00 UT. The images through the 8937 Å filter showed that the effects of the impact already covered roughly 10^8 km^2. The highest intensity was observed in the north-east with a shallow gradient to the south-west. The appearance to the south-west gives the impression of an arc turning through 90° about 4200 km (9 pixels) from the brightest point.

The appearance in the other filters used is less clear. In the 7271 Å filter the contrast between the impact site and the surroundings is quite poor and no structure of the site is immediately apparent. At both 7508 Å and 8290 Å, the site again gives the impression of being extended to the south and west.

The increase in intensity produced by impact D was not so large. Subtracting the average intensity of Jupiter's disk in the methane band at that latitude from data obtained around July 18, 00:00 UT (12 hours after the impact) shows site D to have a similar morphology to that of the impact site H.

If the morphologies of the intensity increases seen in the 8937 Å filter were caused by the transmission of energy through the atmosphere, the velocity of the disturbance would have to have been around 330 (±60) m s^{-1}. There are two alternative explanations, however. Firstly, the impactors entered the atmosphere at an angle of around 45° while the fireball produced was probably directed vertically upwards. The entry of the impactor would therefore have affected the atmosphere at higher latitudes before it was destroyed. However, this allows an estimate of the depth at which the object exploded by dividing by the tangent of the entry angle giving a depth of 0.06 R_J. This is far deeper than predicted by the hydrodynamics models [1]. A second alternative is that the objects broke up before impact with debris entering over a much greater surface area. The impactors did appear to be elongated in images obtained at the beginning of July but, of course, they were not resolved. The difficulty here is to explain why impact sites D and H look so alike with the brightest point in the north-eastern corner when one might expect the debris to be more randomly distributed over the surface.

3.3 *The persistence of impact sites A and E*

The data from July 17 and 18 can be used to compare the brightness of impact site E after 2 Jovian rotations. The results can be seen in Table 3 and show that impact site E appeared to remain constant or possibly increase slightly in brightness at 8937 Å with time during this period. An increase in brightness may indicate cooling and subsequent condensation of gases in the upper atmosphere.

The persistence of the impact sites over several rotations was a major surprise. Figure 2 shows an image taken on the last night of our observations. This night provided excellent seeing (less than 0.7 arcsec) as can be seen from Figure 2. Many impact sites could be seen during the night with complex structures evolving from multiple impacts on the same region. In the centre of Figure 2, however, there is a small spot which is the remnant of impact A, more than 7 days and 17 Jovian rotations after the initial event.

4. Future Work and Conclusions

The main priority at present is to complete the reduction of all images and make an assessment of the morphology of each impact site. The observed

TABLE 3. *The intensity of impact site E through the 8937 Å filter*

Date	Time (UT)	Peak increase in intensity relative to pre-impact (%)	Estimated increase in intensity of 10^8 km^2 area (%)
18 July	03:03	54	13
18 July	23:02	64	16

Figure 2: *The disk of Jupiter on July 23, 1994, 23:17 UT. Impact site A was almost on the sub-solar meridian and can still be seen more than 7 days after the initial impact.*

changes in the brightness of the impact sites are also of considerable interest. The observations through different filters will allow an estimate of the scattering properties of the aerosols produced by the impacts. Models currently being used by us to determine the effects of aerosols on Martian surface photometry will be useful in this study.

Acknowledgements

We would like to thank R.M. West and O. Hainaut for the excellent way in which they have coordinated and supported the observations. We would also like to thank our fellow observers for exciting discussions during the observing period.

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The Distribution of Near-IR Emissions in the Jovian Stratosphere Caused by the SL-9 Impact

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Between July 16 and 31, Jupiter was monitored spectroscopically in the near-IR with the IRSPEC spectrometer at the 3.5-m New Technology Telescope (see Encrenaz et al., this issue). During the week of impacts, the 4.″4 slit was aligned along the parallel of the impact sites (lat.: –44°) allowing a spatial analysis in this direction. Starting on July 23, we also observed the counterpart of the impact region in the northern hemisphere (lat.: +44°) and proceeded with a mapping of the entire planet. Data were recorded in several spectral regions between 2 μm and 5 μm with preference to the regions around the the H_3^+ multiplet at 3.5 μm and the H_2 S(1) quadrupole line at 2.12 μm attributed to the Jovian stratosphere.

1. Observations During the Impact Week (July 16–22, 1994)

On July 16, 23:13 UT, we started observing the phenomena in the Jovian stratosphere resulting from the impacts. The impact regions of fragments A to H were monitored in the ranges 2.107 μm–2.135 μm and 3.501 μm–3.566 μm. Due to bad weather we had to interrupt our observations and could resume only on July 22 after the final impact had taken place. Our last useful observation during the week of impact was taken on July 18, 20:24 UT. However, we were able to obtain spectra at the impact times of fragments B, F, and H. The impact of B was observed at 2.12 μm and H was watched in the 3.5 μm region. For impact F we recorded data in three spectral regions (3.3 μm, 3.5 μm, 2.1 μm) until three hours after impact. No H_3^+ was detected in the 3.5 μm observations of impact regions H and F within about an hour after the event, whereas it was clearly present in more evolved impact regions. For more details on impact H see Encrenaz et al., this issue. Figure 1 shows a spatially resolved spectrum obtained at 2.1 μm about 2 hours after impact F. Since fragment F almost fell on impact site E, both sites lie side by side very close together and can only be distinguished by their distinctly different spectra in the 2.1 μm region. As demonstrated in Figure 2 the spectrum of F is characterized by a strong featureless continuum, whereas the already evolved site E