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Optical imaging of the impact plume on Jupiter from fragment L of comet D/Shoemaker–Levy 9

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ABSTRACT

We report optical CCD imaging and photometry of the impact plume on Jupiter resulting from the destruction of fragment L of D/Shoemaker–Levy 9. The plume appears resolved in several frames, with the largest dimensions appearing similar to those of other plumes imaged by *HST*. The light curve and timings are consistent with an ejection velocity for the plume material of $v \simeq 20$ km s^{-1}. The plume itself was detected by reflected sunlight from dust grains, and the observed fluxes are consistent with an optically thick plume composed of silicates. A large flare in the light curve was observed ~ 7 min after the initial maximum, the cause of which is unclear.

Key words: comets: individual: D/Shoemaker–Levy 9 – planets and satellites: individual: Jupiter.

1 INTRODUCTION

The collision between the fragments of the disrupted comet D/Shoemaker–Levy 9 and the planet Jupiter was the first collision between two major solar system bodies to be observed in any detail. Owing to the orbital geometry at the date of collision, the impacts occurred just on the far side of the planet as viewed from Earth, although there are indications that the bolide phase of the impacts may have been detected by several investigators operating in the infrared (e.g. Nicholson et al. 1995a). In particular the *Galileo* spacecraft was able to observe directly the impacts with its on-board instruments. Subsequent comparison between measured fluxes with the Solid State Imaging (SSI) and the Photo Polarimeter Radiometer (PPR) experiments demonstrated that the impact of fragment L was the most energetic (Martin et al. 1995). Timings of impact-related phenomena are generally given as when they were observed on Earth (i.e. including the light travel time of 42 min, from Jupiter) and we follow the same protocol in this paper. *Galileo* observed the bolide entry into the atmosphere to begin at 22:16:48 UT (Earth time).

The majority of the collisions resulted in large plumes of ejecta appearing above the limb of the planet as observed by the *Hubble Space Telescope* (*HST*) (Hammel et al. 1995).

Infrared light curves showed a complex evolution, with a 'main event' arising from atmospheric heating by re-impacting ejecta (Nicholson et al. 1995a). Unfortunately the *HST* data could not provide a good comparison with the infrared light curves as the plumes were imaged through a succession of filters of different wavelengths. It is of considerable interest then that we obtained monochromatic IR CCD images of Jupiter at the time of the impact of fragment L, and were successful in observing the resulting ejecta plume. This paper describes those observations and their interpretation.

2 OBSERVATIONS

The planet Jupiter was imaged on the night of 1994 July 19 using the 1-m Jacobus Kapteyn Telescope on La Palma. The detector used was a cooled TEK blue-sensitive CCD with pixels 24 μm square. At the cassegrain focus of the telescope, this corresponded to an image scale of 0.31 arcsec pixel^{-1}. The total imaging area of 1024×1024 pixels was subsequently windowed to 512×512 pixels to allow faster readout times. A narrow-band filter of central wavelength 9075 Å and full-width half-maximum 60 Å was used both to minimize the amount of reflected sunlight from the planet and also to maximize the chance of detecting any thermal emission resulting from the collision. The exposure times were 1.5 s for all Jovian images, which was found to give

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~ 30 000 counts pixel^{-1} (half-well capacity) on the disc of the planet.

Images of the planet at this wavelength were continuously obtained between 21:44 and 23:00 UT, covering the expected time of impact of fragment L. At this time Jupiter was at a geocentric distance of 5.177 au, resulting in an image scale of 1160 km pixel^{-1}. Owing to the relatively long readout time of this system, the resulting data set had a temporal resolution of 1–2 min. These images were bias subtracted and flat fielded in the standard manner using calibration frames obtained at the beginning of the night. These and all subsequent image processing operations were performed using the Starlink software package KAPPA (Currie 1992). Before and after this period, observations were also made of the spectrophotometric standard BD + 26 2606 (Oke & Gunn 1983) to allow extinction corrections and absolute flux calibration.

3   REDUCTION AND ANALYSIS OF PLUME IMAGES

Inspection of the raw data revealed a bright feature which appeared on the limb of the planet, brightened and subsequently faded. As this feature occurred at the expected latitude of the impacts, we identified this as the optical ejecta plume resulting from the impact of fragment L. However, scattered light from the image of the planet dominated the background near the limb, preventing detailed inspection of the raw images. The subsequent flux calibration process did not enhance the visibility of the plume, which even at maximum was only 20 per cent brighter than the background (as measured adjacent to the plume) and significantly fainter than the disc of the planet.

To ensure accurate measurement of the plume, it was first necessary to determine which images contained the plume. Using a CCD frame obtained at 22:08:12 UT as a template (i.e. before the bolide entry), all subsequent exposures of the planet were first shifted to be coincident with this image. These were then divided by the template. This resulted in the removal of both the majority of light from the disc of the planet and of the scattered light on the limb, thereby clearly revealing the plume. It was found that the plume first appeared in an image obtained at 22:22:15 UT, and became difficult to identify above the background residuals by 22:37:50 UT. This subset of our data that contains the plume is shown in Fig. 1. It is apparent that in some cases (particularly between 22:33 and 22:35 UT), small changes in the seeing have resulted in comparatively large residuals on the limb, thus hindering inspection of the plume. Note also that, owing to the rapid rotation of Jupiter's clouds, features on the disc move appreciably on time-scales of a few minutes and do not subtract well using this technique (the most prominent residuals on the disc in Fig. 1 are due to the impact site of fragment K).

The plume magnitudes were measured by subtracting the template Jovian image from all images obtained from 22:20 onwards, and then by using the Starlink package PHOTOM (Eaton 1992) to perform aperture photometry on the resulting image. The frames were measured by integrating the detected counts in a circular aperture, 8 pixels (2.5 arcsec) in diameter, centred on the plume position, and then subtract-

ing the mean background measured either side of the plume at the same distance relative to the limb. Thus ensured removal of residual scattered light arising from changes in seeing between the template image and the frame being measured. These counts were then converted to above-atmosphere magnitudes using the photometric calibration discussed above. The resulting fluxes are presented in Table 1 and in graphical form in Fig. 2, with errors dominated by uncertainties in the residual background.

4   DISCUSSION

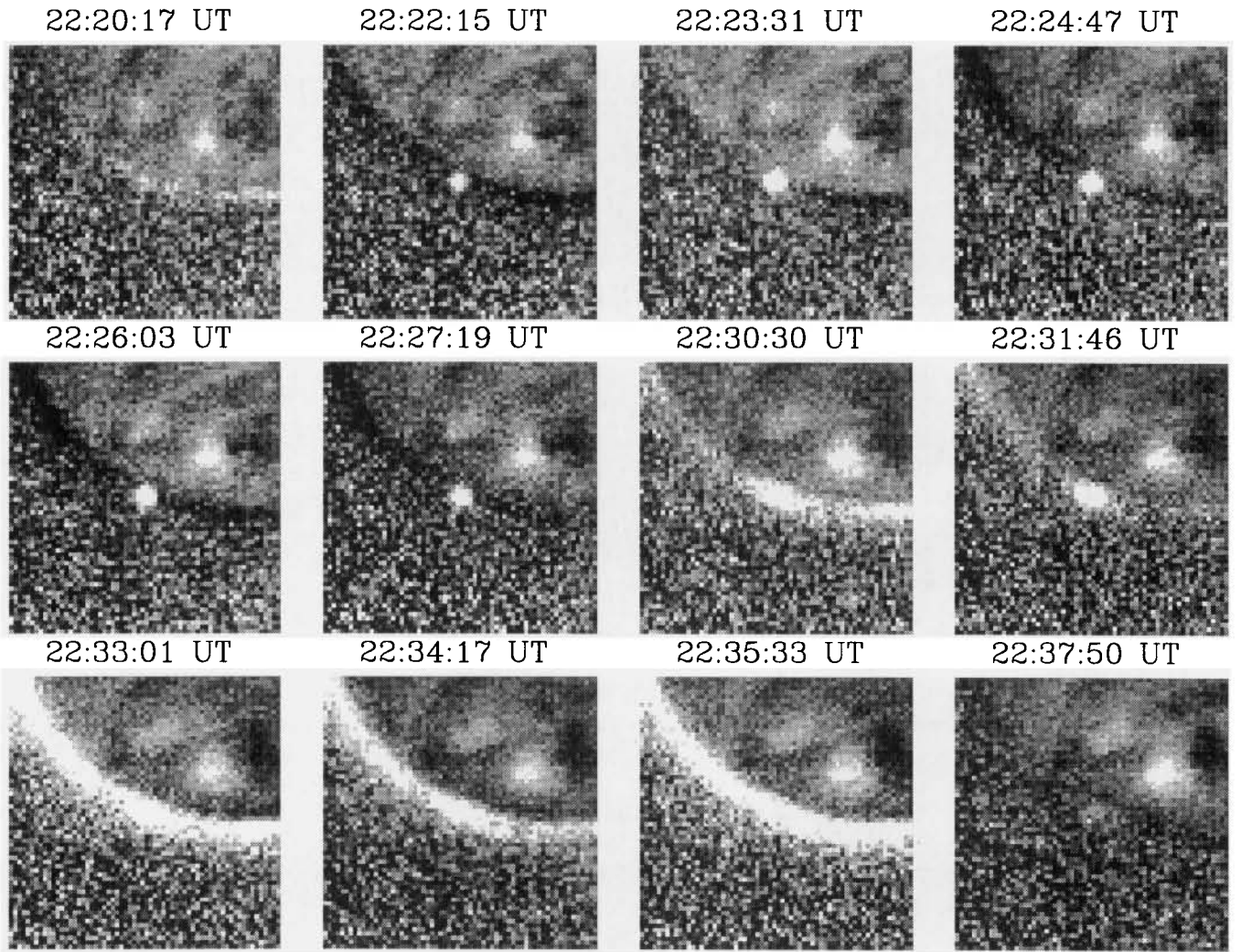### 4.1   Plume morphology and light curve

In all of the images, the size of the plume measured perpendicular to the limb of the planet never exceeds 3–4 pixels, corresponding to a height of ≤4800 km. Taking into account the effects of atmospheric seeing, which will make the plume appear to reach a greater height than in reality, it appears that the L-plume reached a similar, but not significantly higher, altitude than that of the G-plume as measured by *HST* (3300 km; Hammel et al. 1995). In the images obtained after 22:26 UT, the plume itself appears to be resolved in the horizontal direction (i.e. parallel to the Jovian limb). This is demonstrated by the contour plots in Fig. 3. The maximum width of the plume in our data was 9000 ± 1000 km at 22:31:46 UT. Therefore the plume appears to exhibit an overall morphological change in agreement with the intuitive evolution of an ejecta plume. To be specific, the first 3–4 images appear unresolved. After this point, a dome-like shape is apparent, which slowly collapses and flattens on to the limb of the planet. A similar evolution for other impact plumes is shown with much greater clarity in the *HST* images.

Fig. 2 clearly shows the rapid rise in brightness of the visible plume followed by a slower decrease (plus an apparent flare – see below). It can be seen that after the plume disappeared, the flux within our software aperture did not immediately return to zero but appeared instead to remain at a low, but significant, level. A later image obtained by us at 23:15:01 UT, and measured in the same manner, revealed negligible emission, implying that this flux excess is real. We believe that this plateau in the light curve is due to high-altitude impact debris in the atmosphere moving into our software aperture as it rotates over the Jovian limb and becomes visible through reflected sunlight. A similar conclusion was reached by Schleicher et al. (1994), whose own light curve of the event shows a similar effect.

From these values, we can get a remarkably consistent picture of the plume. If we assume that it is composed of hot material forced back up the 'funnel' formed in the atmosphere by the impact, then this material will describe an approximate parabola once clear of the atmosphere. In a simple approach, the height of the plume will be

$$h = \frac{v^2 \sin^2 \alpha}{2g},$$

where α is the angle of the funnel to the surface, v the ejection speed, and g the surface gravity of Jupiter. Solving for the entrance angle of 45°, the ejection speed is $v \simeq 20$ km s^{-1}. The time taken for the plume to reach its maximum

22:20:17 UT	22:22:15 UT	22:23:31 UT	22:24:47 UT
22:26:03 UT	22:27:19 UT	22:30:30 UT	22:31:46 UT
22:33:01 UT	22:34:17 UT	22:35:33 UT	22:37:50 UT

Figure 1. Enhanced CCD images of the Jovian limb revealing the plume from the impact of fragment L. Each image is a 64×64 pixel subset centred on the plume.

Table 1. L-plume fluxes at 9069 Å.

| Time (UT)	Flux (ergs/sec/cm²/Å)
22:20:17	$(6.34 \pm 3.57) \times 10^{-14}$
22:22:15	$(3.68 \pm 0.42) \times 10^{-13}$
22:23:31	$(7.90 \pm 1.20) \times 10^{-13}$
22:24:47	$(1.00 \pm 0.13) \times 10^{-12}$
22:26:03	$(9.77 \pm 1.02) \times 10^{-13}$
22:27:19	$(7.83 \pm 1.14) \times 10^{-13}$
22:30:30	$(6.95 \pm 1.27) \times 10^{-13}$
22:31:46	$(1.22 \pm 0.87) \times 10^{-12}$
22:33:01	$(6.11 \pm 0.64) \times 10^{-13}$
22:34:17	$(4.07 \pm 0.72) \times 10^{-13}$
22:35:33	$(4.00 \pm 0.73) \times 10^{-13}$
22:37:50	$(2.87 \pm 0.92) \times 10^{-13}$
22:39:06	$(3.58 \pm 1.19) \times 10^{-13}$
22:40:22	$(2.87 \pm 0.87) \times 10^{-13}$
22:41:38	$(2.84 \pm 0.46) \times 10^{-13}$
22:42:54	$(3.61 \pm 1.02) \times 10^{-13}$
22:59:43	$(3.45 \pm 1.37) \times 10^{-13}$

height is then given by

$$t_{max} = \frac{v \sin \alpha}{g},$$

resulting in $t_{max} \simeq 10$ min, or approximately 22:26 UT. This agrees with the observed time of maximum brightness of the plume. The ejecta will have re-entered the atmosphere by 22:36 UT, again in good agreement with our observations.

4.2 Plume emission mechanisms

A fundamental question to ask is: what is the mechanism by which we are observing the impact plume? The three possibilities are line radiation from excited atomic and molecular species, thermal continuum radiation from the gas, or reflected sunlight. Below we discuss each possibility in turn.

First, the filter used to obtain these measurements is primarily used for isolating the S III emission at 9069 Å in planetary nebulae. Optical spectra obtained of this impact by
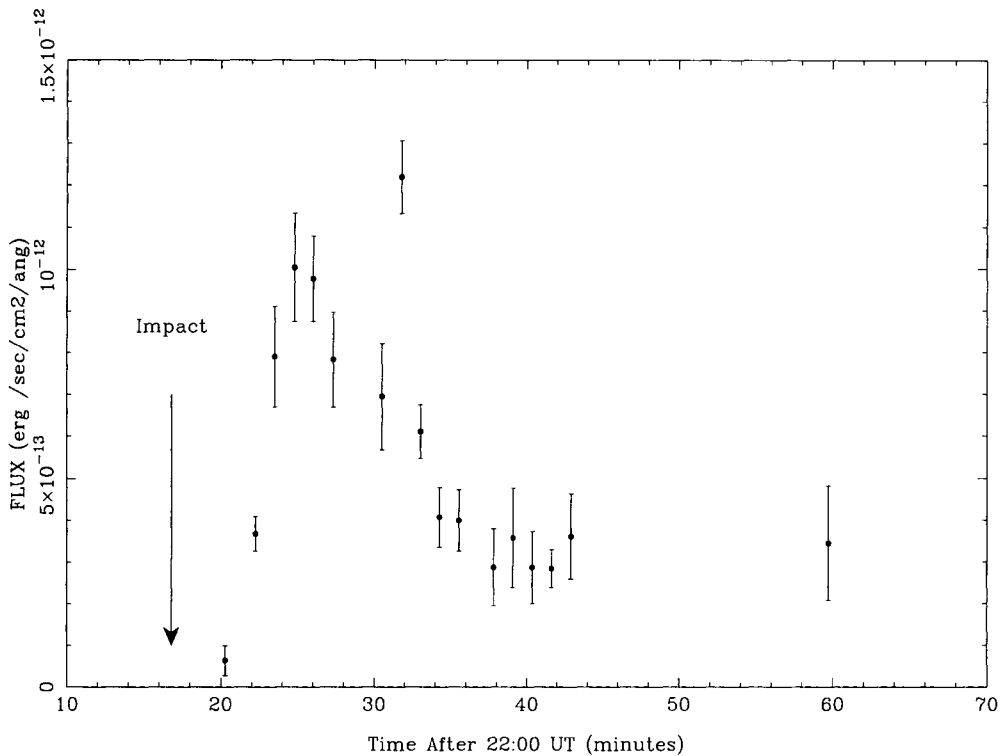
Figure 2. Total fluxes measured at the plume on the Jovian limb. The time of impact determined by *Galileo* is indicated by an arrow.
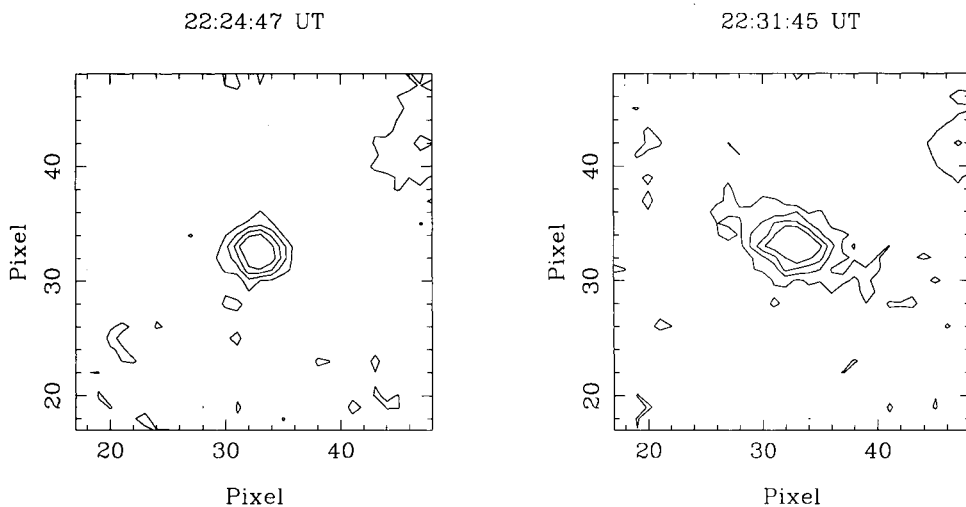
Figure 3. Contour maps of the plume images from Fig. 1 at the time of the first and second maxima in the light curve. Contours are at pixel values 1.05, 1.15, 1.25 and 1.35. Although the second image shows a lateral spreading along the Jovian limb, both have centres coincident with each other.

both the authors and independent observers show emission solely due to neutral atomic species, with no ionized elements or molecular emissions present (Fitzsimmons et al. 1995; Roos-Serote et al. 1995). A line search conducted using Moore (1972) showed that the strongest neutral atomic lines contained in the bandpass are due to multiplet 3 of C_I. However, the levels involved in these transitions are too much higher than those observed by the above investigators to have been excited, and are highly unlikely to have con-

tributed any emission. Therefore we conclude that the plume is seen by continuum radiation rather than line emission.

By combining the flux detected on Earth with the emitting surface area of the plume, an equivalent blackbody temperature may be derived. We assume that the plume has a hemispherical shape of radius $r \approx 2000$ km at 22:24 UT when it is barely resolved, corresponding to the time of the first peak in the light curve (see Section 4.3). The temperature is then derived by equating the specific intensity derived from the

flux f_λ measured at Earth with that of a theoretical blackbody at temperature T.

$$f_\lambda \frac{\Delta^2}{r^2} = \frac{2hc}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1},$$

where Δ is the Earth–Jupiter distance, and the other symbols having their usual meaning. For the time of first maximum observed in the plume light curve, a temperature of $T = 850$ K is derived. This temperature is of the order predicted in pre-impact models (Takata et al. 1995), and is also similar to that found in other impacts (Nicholson et al. 1995b). However, this temperature would produce a flux at 12 μm of $f_\lambda = 8 \times 10^{-11}$ erg s^{-1} cm^{-2} Å^{-1}, which is an order of magnitude more than that observed by Lagage et al. (1995), thereby implying a spectrum inconsistent with an 850 K blackbody spectrum.

We therefore conclude that the observed emission is due to reflected sunlight from particulate matter (dust grains) formed within the plume itself. This hypothesis is strongly supported on the grounds that no emission was detected until three minutes after *Galileo* recorded the bolide entry, implying that the ejecta had to reach large heights before detection. We note that in *HST* images of similar impacts, the plume is observed to be in sunlight. As theoretical models show that the bolide will be completely vaporized during impact, this material must have condensed within the ejecta plume during its early evolution. Hasegawa, Takeuchi & Watanabe (1995) show that magnesium silicate grains could easily form with diameters of 0.1–10 μm within the first 100 s after impact.

In this case, for the same stage of plume evolution considered above, the product of the albedo of the dust grains p, together with the total cross-sectional area C, is found from the relationship derived by Russell (1916) to be

$$pC = 6.8 \times 10^5 \text{ km}^2.$$

For the sake of illustration, we assume that the dust grains are composed of magnesium silicates such as olivines and pyroxenes ($Mg_2Si_2O_6$, Mg_2SiO_4). These minerals possess a deep absorption band at ~ 0.9 μm, resulting in an albedo of $\simeq 0.1$ at the wavelength observed. This gives a total reflecting cross-sectional area of ~ 7×10^6 km^2, in excellent agreement with the plume cross-section of 6×10^6 km^2. Therefore we conclude that the plume was optically thick at visible wavelengths, with all lines of sight occupied by condensed dust grains.

Finally, we note that if the plume had near solar colours, then it would have had a visual magnitude of $m_V \sim 8$, implying that it would have been visible to amateur astronomers observing at high power from a good site. We are not aware of any reported sightings of plumes from visual observers of this or any other large impact, but this may be due to the large problem of scattered light from the disc of Jupiter as discussed above.

4.3 The flare

As shown in Fig. 2, the observed flux from the plume exhibited an evolution more complex than might be expected. The first three images of the plume showed a steady increase in

brightness until a maximum was reached at 22:24:47 UT. This was presumably caused by a number of effects, primarily the expansion of the plume into space above the Jovian limb, where the expansion of the plume increased the visible surface area, and also the rotation of the planet, which brought more of it into view. Note that the plume did not become visible until > 3.5 min after the first detection by the *Galileo* spacecraft. As this time interval was longer than the grain formation time discussed in Section 4.1, such a process should not have influenced this part of the light curve.

Beyond this point, the brightness should then start diminishing as the ejecta begins to fall back on to Jupiter on ballistic trajectories. Although this appears initially to be the case, a large flare occurs in the detected flux at 22:31:46 UT, which is 20 per cent higher than the previous maximum and $\simeq 100$ per cent brighter than the underlying trend. This is not a spurious result arising from incorrect calibration of this image; the effect is apparent in the raw data. Also, the brightness of Jovian disc remains constant at this time as well, demonstrating that it is the plume alone that brightens and that it is not due to varying atmospheric transparency. Finally, Schleicher et al. (1994) have independently observed the same brightening in their images of the L plume obtained at 8920 Å, confirming its existence. Lindgren (in preparation) have also obtained broad-band V images which demonstrate a double-peaked light curve.

The data show that the flare occurs in the same place as the initial plume within the resolution of the images, also observed shown by Schleicher et al. This is demonstrated in Fig. 3, and rules out extra emission caused by ejecta re-entering the Jovian atmosphere, as this would lead to preferential brightening of the lower portion of the plume. A light curve for the L impact at 11.9 μm has been published by Lagage et al. (1995), which only shows a broad peak at about 22:30 UT, and is interpreted as thermal emission from the ejecta re-entering the Jovian atmosphere. Given the sharpness of the optical flare compared with the much longer time span of the infrared peak, it is difficult to ascribe both effects to the same process.

The spectra of Fitzsimmons et al. (1995) show no peculiar brightening of emission lines at this time, again ruling out line emission as the cause. Finally, it is highly improbable that we witnessed a double impact, with one plume being seen superimposed on the other. To produce the same detected luminosity for each plume would have required impactors of similar mass, yet the *Galileo* PPR experiment only detected the bolide entry owing to fragment L, although it recorded data for 10 min afterwards. Given that the time separating the two light curve maxima is only $\simeq 7$ min, this rules out the possibility of a double impact.

We note that the time of the flare is coincident with the appearance of the impact point itself on the limb as seen from Earth. The flare might then be due to the appearance of the site combined with the rapidly cooling thermal emission. However, it is not obvious from where such emission would originate and how it would remain radiating strongly > 10 min after impact. The remaining possibilities are that the flare is due to an increase either in the cross-sectional area of the reflecting grains or an increase in their albedo due to a second condensation stage. Why this should occur is again not readily apparent.

Unfortunately it is not possible to compare this event with other impacts, as the L plume is the only one with a published light curve at wavelengths <1 μm. Similar flares have not to date been reported in the near-infrared light curves of any impacts which may be dominated by reflected light (for example Watanabe et al. 1995), although no such observations have as yet been reported for the L plume. In summary then, we cannot conclude yet whether this aspect of the L-fragement impact was unique, or whether it might have been a general phenomenon in the impacts.

5   CONCLUSIONS

In this paper we have reported our observations of the plume resulting from the impact of fragment L of comet D/Shoemaker–Levy 9 on Jupiter. The plume appears to be at least partly resolved in our data at late stages arising from the spreading of the ejecta along the limb of the planet as seen from Earth, with dimensions similar to those seen in other impacts. The data imply an ejection velocity of $\simeq 20$ km s^{-1}. From our data alone we cannot rule out thermal emission as an explanation for the visibility of the plume, however, from comparison with infrared data, the most likely cause was reflected sunlight from condensed silicates. In this case the plume was optically thick. A second brighter maximum (the flare) cannot be explained as yet, but may have been caused by either a second stage of condensation or by a change in the mean albedo of the particles. Confirmation or rejection of these hypotheses must await the release of fully calibrated data by other investigators.

ACKNOWLEDGMENTS

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