On the Reflections off the Jovian Satellites of the Impact of Comet D/Shoemaker-Levy 9 with Jupiter

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L. M. Woodney, M. F. A'Hearn, R. Meier † , D. D. Wellnitz

Department of Astronomy, University of Maryland, College Park, MD 20742-2421

Ph: 301-405-1561, Fax: 301-314-9067, Email: `woodney@astro.umd.edu`

Ph: 301-405-6076, Fax: 301-314-9067, Email: `ma@astro.umd.edu`

Ph: 808-956-8312, Fax: 808-988-2790, Email: `meier@uhifa.ifa.hawaii.edu`

Ph: 301-405-1546, Fax: 301-314-9067, Email: `wellnitz@astro.umd.edu`

S. Takeuchi

Department of Earth System Science, Fukuoka University, Nanakuma, Jyonan-ku, Fukuoka 814-0180, JAPAN

Ph: +81-92-871-6631 ext.6196, Fax: +81-92-865-6030, E-mail: `se039153@ssat.fukuoka-u.ac.jp`

T. Smith, A. Verveer, R. Martin

Perth Observatory, Walnut Road, Bickley 6076, Western Australia

Ph: 8-9293-8255, Fax: 8-9293-8138, Email: `rmartin@physics.uwa.edu.au`

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† Now at *Institute of Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI 96822*

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Editorial Correspondence:	L. M. Woodney

L. M. Woodney
Department of Astronomy
Comp. Sp. Sci. Bldg.
University of Maryland
College Park, MD 20742-2421

Abstract

Observations of the Galilean satellites during the impact of D/Shoemaker-Levy 9 with Jupiter are presented. The data for impacts D, E and K have been analyzed for reflections of the impact events off the satellites and several possible detections are reported. These events do not have high enough signal-to-noise to be confirmed as real events without evidence from a second site. However, we show that it is reasonable for some but not all of them to be actual reflections, if the observations are of line emission due to the ablation of the nucleus during the meteor phase. We also present evidence that the two precursor events occurred closer together in time for the smaller fragments, suggesting a correlation between fragment size and depth of penetration into the Jovian atmosphere and we apply this to the case of impact D.

Keywords: Comets, S-L9, Satellites of Jupiter

1. Introduction

The impact of comet D/Shoemaker-Levy 9 (S-L9) with Jupiter provided many surprises, including the lack of obvious reflections off the satellites from the impact flashes. Since impacts were to occur behind the limb of Jupiter as seen from Earth, it had been predicted that observing these reflections would be one of the best ways to learn the timing and the luminosity of the flashes. Io should have been the best reflector; while Amalthea is closer to Jupiter, its smaller size and low albedo make it a less efficient reflector. Europa's greater distance from Jupiter made it a second choice to Io.

It is clear that the flashes were far fainter at visible wavelengths than had been predicted. In the infrared observations of the limb of Jupiter, typically two small precursor flashes were seen before the largest brightening. The first precursor has been interpreted as the bolide entry, the second precursor as the rise of the fireball above the limb, and the final event as the fallback of material into the Jovian atmosphere (*Zahnle and MacLow*, 1995). Of the many groups looking for flashes reflected by satellites, no one has been able to report anything but tenuous detections near the observational limits. One such detection is that of Consolmagno and Menard (1995), who observed from Italy. They reported a brief reddening of Io near the impact time of H as well as a coincidence in time between their observations and those of a third observer in Kiev near the impact of Q. For any of the reports to be considered real events, there will have to be corroboration between two or more observers and consistency with a physical model for the emission. However, the possible detections also can not be ruled out without a definite non-detection from a second observer. We will report here on our attempts to observe flashes during three of the impacts, including several possible detections (D, E, and K). This analysis will show the precision needed for a positive result and can be used to set constraints on other observations.

2. Observations

The Maryland-Perth team observed the impacts from two sites in Western Australia. Five impacts were predicted to be visible from these sites – including that of fragment K, the only impact which would occur while a satellite was in eclipse but visible from earth if illuminated. For the other impacts the flash had to be observed against the large background of reflected Sunlight. The flashes were expected to be small compared to the reflected solar component (one to ten percent), so the best opportunity to observe an effect was during an eclipse.

At the Perth Observatory, a CCD on the 24-inch (61-cm) telescope was used to image the limb of Jupiter during events E, K, and N. We also used a portable high-speed photometer and 14-inch Celestron telescope to obtain photometry of Io or Europa around the expected impact times of D, E, K, N, and P2. Since July is one of the rainiest months of the year in Perth, it was decided to take this portable system to Mt. Singleton, approximately 450 km northeast of Perth, where six years worth of weather statistics told us the chances of clear sky were twice as high (*Birch*, priv. comm.), although for these observations the weather was as good in Perth as at Mt. Singleton.

With the CCD, the limb of Jupiter was observed by placing an occulting disk in front of most of the planet, leaving only the limb visible. For each impact a narrow band filter was also used to reduce the light from Jupiter, although the choice of this filter was different for each event. In addition to the limb, some of the images also include either Io or Europa in the field of view (Table I). The hope was that this would allow us to observe any optical flash that was visible above the limb as well as any flashes reflected by cometary dust or the moons when in the field of view. The dominant source of error in these observations is the variability of the scattered light from Jupiter.

The photometer used on Mt. Singleton had a bi-alkali photocathode and the observations were made with no filter. The resultant bandpass of the telescope and photometer system ranged from 312 to 615 nm with an effective wavelength of 453 nm. On a perfectly clear night we obtained continuous lightcurves of Io at the predicted times of the impacts of fragments D and E. Mechanical problems during K, N and P2 left large gaps in the time coverage which severely limit the usefulness of the data.

For each observation the appropriate moon was centered in a thirty-arcsecond aperture. Tracking was done by an observer looking through a five-inch finder telescope and using the hand paddle to track on the moon. This tracking method, combined with the Jovian scattered light, is one of the larger sources of error in the photometer data. Motion of the moon within the aperture caused variations on the order of 5% as more or less scattered light entered the aperture. The moon was also occasionally lost from the aperture for brief periods. As many tracking errors as possible were noted by hand on the photometer strip chart, so that they could later be distinguished from real results.

A voltage-to-frequency converter was used to record the data onto audio tapes. The frequencies were then converted to digital data at a later time. In order to optimize the system for detecting small events, we set the gain as high as possible. This means that the moon alone was very close to the saturation point of the voltage to frequency converter. When this converter is saturated the frequency goes to zero, which leads to low values for all saturations when the data are digitized. This leads to an ambiguity between low values due to saturations and low values due to the loss of the moon from the aperture. Values which are below the sky level are clearly saturated; however, some portion of all low spikes which are still above the sky can be attributed to either saturation or loss of a portion of the moon from the aperture.

Many such saturations are seen in the data for event E (Fig. 1). This is due to winds buffeting the telescope during these observations. The wind made it impossible to keep Io centered in the aperture and led to variable, strong contamination by scattered light from Jupiter in the aperture. Since we were working so close to the limit of the instrument the scattered light was enough to saturate it.

3. Flashes Seen by Galileo

To understand what we expect to see in reflection from the Jovian satellites, we need to consider the measurements made by the Galileo spacecraft. Its direct view of the impacts gave the best measurements of the total luminosity of the entry effects because they are not complicated by the effects of observing geometry. We discuss these results first in order to simplify the subsequent discussion of our own observations.

The color temperatures and lightcurves of the Galileo data indicate that its instruments observed the last phase of the bolide entry, which was extremely hot and blue, lasting a few seconds, followed by a rising fireball which expanded and cooled with time. Ground based observers using infrared detectors generally saw a short precursor flash 10 to 40 seconds before the Galileo detection. Therefore, it has been interpreted that the ground based observers were seeing the early phase of the bolide entry before it disappeared behind the limb of Jupiter. The second precursor event seen by the ground based observers would then be the fireball rising above the limb, and the very bright, long duration main event, was the splashback of the fireball material (*e.g. Zahnle and MacLow*, 1995).

To decide what these observations mean for our flash measurements however, we are primarily concerned with determining the luminosity of what Galileo saw, and how this relates to the characteristics of each fragment. For this purpose, following the method of A'Hearn *et al.*(1995), we will consider the measurements of lightcurves from two instruments, the Solid State Imaging Camera (SSI) (*Chapman et al*, 1995) and the Photopolarimeter Radiometer (PPR) (*Martin et al*, 1995). The SSI observed events N and W at 889 nm and K at 550 nm, while the PPR observed G, H, L, and Q1 at 945 nm. To compare the measurements from different instruments it is useful to first convert them to the same wavelength.

Assuming a black-body emission at 8000K we can convert the peak emission of all of the lightcurves to 945 nm. This temperature is derived from one instance in which there were simultaneous observations with UVS and PPR, for impact G (Carlson *et al.*1997). Though this temperature does not apply to all of the impacts' effects throughout their evolution, it is applicable to the initial phase observed by Galileo, so is a reasonable choice for the peak emission. This correction reduces the observed flux by between 70 and 10 percent, depending on the wavelength of the observation. Though the Galileo Near Infrared Mapping Spectrometer (NIMS) data show that the fireball event is fit fairly well by a blackbody which is cooling with time (*Carlson et al.*, 1997), it is actually rather unlikely that the bolide event emits as a black-body and alternative approaches to comparing data taken at various wavelengths will be discussed later.

We would like to find a correlation between the luminosity of the impacts observed by Galileo and the cometary fragments so that we may predict what luminosity to expect from the impacts which were not observed by Galileo. A'Hearn *et al* (1995) took the Galileo lightcurves, which were corrected to 945 nm, and converted both the peak brightness and the integral of the brightness over the entire lightcurve to luminosities at the impact site assuming isotropic emission over 2π steradians. In Fig. 2 these energies are plotted *vs.* the nuclear magnitudes of the fragments as measured with HST by Weaver *et al* (1995). If we can assume that the nuclear magnitude is proportional to the size of the nucleus, then the lines that have been overplotted on the data with slopes of 1 and 3/2 represent the proportionality that we would expect to see between the luminosity and the cross section of the nucleus, and the luminosity and the mass of the nucleus, respectively. This plot indicates that the peak luminosity is proportional to the cross section while the integrated luminosity is proportional to the mass, though there is a large amount of scatter (approximately a factor of 7 peak to peak). This scatter suggests that the nuclei of the separate fragments represent a heterogeneous collection of objects.

Having shown that there is a proportionality between the nuclear magnitudes and the luminosity, albeit with a great deal of scatter, we still need to find a way to predict the luminosity of impacts not observed by Galileo. One way to do this is to compare the sizes of the spots that scarred the surface of Jupiter after the impacts. It is reasonable to assume that the size of a spot corresponds to the impact energy and so can be scaled to the integrated luminosity of the impact. In Fig. 3, from A'Hearn *et al* (1995), the spot classification scheme of Hammel *et al* (1995) is plotted against the fragment brightness. The linear spacing of the classes has been arbitrarily assigned and class 4 are upper limits since no detectable spot was seen. There is clearly a trend in spot size with nuclear magnitude, though again we see a great deal of scatter. By using this figure with the previous one we can estimate what the red luminosity of unobserved impacts should have been. Therefore we can predict that the impact of D should have produced a larger than average luminosity, i.e. above the line in Fig. 2, while E should have had an integrated luminosity close to average, i.e. close to the slope 3/2 line in Fig. 2.

4. Photometry of Impacts D and E

4.1 Calculation of Flash Luminosity

During impacts D and E we were observing a sunlit Io with a blue sensitive photometer. In each case we had hoped to observe the flash as a percentage increase in the brightness of the moon. In each case we have a brightening at a plausible time, but to determine whether these are detections or upper limits we must first consider how to interpret these data.

To convert the observed flux increases into flash luminosities we must first calculate the flux from the sun which is normally reflected from Io; then the flux reflected due to the flash is the solar reflected flux times the percent increase in brightness of Io.

We obtain the irradiance of the Sun incident on Io by taking a weighted average of the solar spectrum multiplied by the sensitivity of our system across the bandpass. We used the solar intensities given in Neckel and Labs (1984) and Labs et al. (1987) and found that the effective irradiance of the sun in our bandpass is 1.63 W m^{-2} nm^{-1} at 1 AU.

The solar flux which is reflected from Io is reduced by Io's albedo and the solar phase function. This phase effect is a function of the Sun-Io-Earth angle (α) and is dependent on both the fraction of the illuminated disk and the reflective properties of the moon's surface (Fig. 4). Since the phase function has a dependence on the reflective properties of the surface, it changes not only with α, but with wavelength as well. For this phase function, $P_{Io}(\alpha)$, we will use the Lumme and Bowell (1981a) model as is described in the next section.

The flux reflected from Io due to the flash is then

$$F_{reflected} = \frac{I_{\odot}}{d^2_{\odot,Io}} \cdot Albedo_{Io} \cdot P_{Io}(\alpha) \cdot f,$$

where $I_{\odot}$ is the effective solar irradiance at 453 nm, $d_{\odot,Io}$ is the distance from the sun to Io in AU and f is the percent increase in the brightness of Io. The value we are interested in deriving is not what was reflected from Io, however, but what was emitted from the surface of Jupiter. The flux which is reflected from Io is also

$$F_{reflected} = \frac{L_{flash}}{2\pi d^2_{Io,impact}} \cdot Albedo_{Io} \cdot P_{Io}(\beta),$$

where L_{flash} is the luminosity of the flash, $d^2_{Io,impact}$ is the distance between Io and the impact point, and $P_{Io}(\beta)$ is the phase function which varies with the Impact-Io-Earth angle (β). We can combine the above two equations to derive the luminosity of the flash,

$$L_{flash} = \frac{I_{\odot} \cdot P_{Io}(\alpha) \cdot f}{P_{Io}(\beta) \cdot d^2_{\odot,Io}} \cdot 2\pi d^2_{io,impact}.$$

4.2 The Phase Function of Io

The amount of light reflected from an object is a function of the phase angle and is dependent on shadowing and surface composition as well. For Io, this function can only be measured for phase angles of 12° or less. Since the impact phase angles of our observations are at $\beta > 100°$ we can not use the phase function derived from direct observations (*Morrison and Morrison*, 1977), but turn to a theoretical model instead.

Lumme and Bowell (1981a) have developed a model to describe scattering from atmosphereless planetary surfaces which applies to large phase angles. Though Io does have a tenuous atmosphere, it is not significant enough to affect the results; Lumme and Bowell (1981b) were able to successfully fit their model to the available data. Their phase function is

$$P(\beta) = (1 - Q)P_1(\beta) + QP_M(\beta),$$

where Q is the ratio of multiply scattered light to all scattered light as measured at opposition, and

$$P_1(\beta) = P_S(\beta)P_R(\beta)P_P(\beta),$$

the product of the phase functions due to shadowing ($P_S(\beta)$), roughness ($P_R(\beta)$), and of a single particle ($P_P(\beta)$). $P_M(\beta)$ is the phase function due to multiple scattering and for phase angles between 0 and π can be written as,

$$P_M(\beta) \approx (1/\pi)[\sin\beta + (\pi - \beta)\cos\beta].$$

$P_1(\beta)$ is complicated to calculate, but can be approximated as $exp[-3.343(\tan(.5\beta))^{0.632}]$ (*Lumme and Bowell*, 1981b). Lumme and Bowell (1981b) have computed that $Q = 0.422$ for Io in the B bandpass. We will use the phase function that has been fit for the B filter since this is closest to our bandpass for the observations of D and E.

4.3 Impact D Results

We had photometric conditions for all of our observations with the photometer. The data near the time of impact D, however, provided the only set taken under the additional conditions of good tracking due to lack of wind and no mechanical failures. This makes it the best data series we have. No flashes were large enough to be seen in the strip chart produced at the time of the observation. However, the digitized data were carefully inspected for the several minutes around the time of the precursor flash reported by the observers at the Anglo-Australian Telescope (AAT) (*Meadows*, 1995). The AAT spectral imaging had a 1.5 second sampling rate, and scanned the disk of Jupiter every two minutes. Thus they had very high time accuracy, but large gaps between times when the impact site was obeserved.

A typical infrared lightcurve of the brighter impacts shows two lower intensity precursor events before the bright main event [*e.g. Nicholson*, 1995; *Takeuchi*, 1995]. Typically the onset of the first precursor preceded the second by about 60 seconds and was then followed by the main event three to five minutes later. The two minute gaps between the AAT observations makes it impossible to confirm which precursor event was observed, though its timing is consistent with being the second precursor.

At 11:54:20 UT, 26 seconds before an infrared precursor flash was first observed at the AAT, a very small rise is seen to begin (Fig. 5). Though this is a much shorter time than that between any previously reported precursor events, we present evidence in section 6 that precursor event timing is related to fragment size. Therefore this short separation between precursors is not unexpected for a small fragment like D.

What distinguishes this event from other noise of the same magnitude is that it is a consistent trend over several seconds. It rises over approximately three seconds, stays peaked at 7% above average for almost two seconds, and then quickly drops back. A trend of this duration is rare in the noise, but it is difficult to determine whether this is a flash without confirmation from another site.

For impact D, the Io-impact distance was 3.9×10^5 km, $\beta = 116.8°$ and $P_{Io}(\beta) = 0.06$. Using this information we find a peak luminosity of 4.59×10^{23} erg s^{-1} nm^{-1} at 422 nm.

There are several ways we can compare this to the Galileo results. Galileo did not observe the impact of D, but we can see from Fig. 3 that fragments D and N are similar in both spot class and fragment brightness. Therefore, we may expect that their impact luminosity was similar as well, and Galileo did observe N with the SSI camera.

To compare the Galileo observation at 945 nm to our observation at 422 nm, we must transform the Galileo data to our wavelength. We can do this with either a blackbody fit as in the previous section, or we can use a linear fit. If we use an 8000 K blackbody, the Galileo data transforms to 6.4×10^{19} erg s^{-1} nm^{-1} at 422 nm, several orders of magnitude lower than our observation. Of the two possible flashes we observed, however, this one looks the most real, both in the shape of its lightcurve and in its timing.

However, if what we are looking at is the bolide flash, there is no reason to expect it should have a blackbody spectrum, and a linear fit to the Galileo data is equally valid. We can fit a slope to the G impact where there are simultaneous measurements at three wavelengths. Using this slope we can then extrapolate the luminosity of other fragments at other wavelengths. Using this linear fit, we find that N would have a luminosity of 1.1×10^{20} erg s^{-1} nm^{-1} at 422 nm, still several orders of magnitude lower than our measured luminosity.

This comparison does not yet rule out the possibility that we have observed a flash. Spectra of Comet Halley fragment meteors in Earth's atmosphere are dominated by Calcium and Magnesium emission lines near 400 nm (*Halliday*, 1987). These lines are not atmospheric, but originate from material sublimating from the comet fragments, so presumably similar lines would be present whether the comet broke up in Earth's atmosphere or Jupiter's.

Spectroscopy of the impact sites revealed both Mg and Ca [*Noll et al.*, 1995; *Costa et al.*, 1997]. Both sets of authors postulate that these and other metals observed originate from cometary material, as they do not ordinarily exist in the Jovian upper atmosphere. Therefore the metals were either deposited as the comet ablated during entry, or were lifted back up by the plume.

To estimate whether the observed luminosities could reasonably be accounted for by line emission, we use an analysis method common in the study of meteors in earth's atmosphere. It has been observed that there is a relationship between the luminosity of a meteor and its kinetic energy. This relation is

$$Lt = \beta \frac{1}{2} m v^2,$$

i.e., the integral of the luminosity over time is equal to a luminous efficiency,β, times the kinetic energy of the meteor (*Öpik*, 1958).

There has been much debate over the value of β (*e.g. Halliday et al.(1981), Friichtenicht et al.(1973)*), but since we are observing comet fragments we will elect to use those values of β chosen by Halliday (1987) for the analysis of spectra of meteors from Halley's Comet. These are given as 0.01 or less for Photographic Blue, and 0.02 for Photographic Panchromatic.

To scale these values to our bandpasses and to a Jovian Hydrogen atmosphere instead of the Earth's Nitrogen/Oxygen atmosphere, we have converted the above efficiencies to an efficiency per bright line. Meteor spectra are widely variable, with many multiplets of both atmospheric and meteoroid atoms and ions appearing with varying brightness from spectrum to spectrum. However, there are a few bright lines from Ca II, Mg I, Mg II, Na I, O I and N I that tend to dominate the spectrum and contribute most of the luminosity. Fe I and Fe II lines have been found to occasionally dominate meteor spectra, but since they are weak from the Halley fragments we will assume they are weak from the SL9 fragments [*Bronshten*, 1983; *Halliday*, 1987].

We counted the number of the above bright metal and atmospheric lines in each of the Photographic Blue and Panchromatic bandpasses to determine a luminous efficiency of approximately 0.003 per line. We then similarly calculated how many of those lines plus Hydrogen Balmer series lines would appear in our bandpasses to determine a luminous efficiency for each of our bandpasses, finding $\beta = 0.02$ for the photometer and $\beta = 0.009$ for the r filter and CCD. Using a velocity of 61.29 km/sec (*Chodas et al.*, 1996), we found an ablated mass of 5.6×10^{14} g. This would indicate that a large fraction of the mass of the fragment ablated during the meteor phase if we observed a real flash. This would be consistent with the predictions of Sekanina (1993) (*see also Bronshten*, 1983). These results are summarized in Table 2.

4.4 Impact E Results

For the impact of E we have both photometry of Io and CCD imaging of the limb. The CCD images are 2-second exposures taken approximately every three seconds. Unfortunately, to have the CCD operate at this duty cycle, we could not include Io in the frames. Our data alone show no evidence for any flashes. As noted above, our E photometric data include too many saturations to be able to examine the data for a flash which would stand on its own. A report from India, however, encouraged us to examine our data more carefully. At the IAU meeting in August 1994, N. Raghavan, of the Nehru Planetarium in New Delhi, reported recording a flash off Io which started at 15:14:42 UT, and lasted three seconds. This was recorded on a trailed photograph, with an effective wavelength near 500nm.

Our data from the high-speed photometer for E are saturated from 15:14:40 to 15:14:46 (Fig. 1). With no information about a flash we would have attributed this to scattered light from Jupiter. However, since it does occur at the same time as the suggested flash, it is possible that the last few seconds of the saturated data are due to this flash. If this is true, we can estimate from the spiky nature of the data that it is just barely saturated. If we assume the flash is at the saturation level, then it is 15% of the brightness of Io. This is a surprisingly large number when compared to Galileo's observations, but not inconsistent with the photograph. Raghavan (1997) obtains a peak flash of 23.8% of the brightness of Io from the photograph.

To find the luminosity we use the same calculations as for D. The Io-impact distance was 4×10^5 km, $\beta = 153°$, and $P_{Io}(\beta) = 5\times10^{-3}$. This results in a a luminosity of 1.1×10^{25} ergs sec^{-1} nm^{-1} at 422nm.

Galileo did not observe the impact of E, but from Fig. 3, we expect the luminosity of E to be similar to that of H, which was observed by the PPR instrument. In this case we need to transform the Galileo measurement from 945 nm to 422 nm. If we assume an 8000K blackbody, impact H would have a luminosity of 3.0×10^{20} ergs sec^{-1} nm^{-1}, and in this case a linear fit would yield 1.6×10^{20} ergs sec^{-1} nm^{-1}, 5 orders of magnitude below our recorded value.

We have previously reported a possible second co-incident event in one of our CCD images (*Woodney et al.*, 1994). It is a two pixel event seen just off the limb of Jupiter in a 1.62 second exposure centered on 15:14:44 UT. Io was not in the field of view. Since these bright pixels were at the the expected impact latitude of fragment E, -43.5°, we investigated it as a possible flash off a concentration of cometary particles. However, since this object would be closer to Jupiter than to Io, a careful consideration of light travel times reveals that we would expect to see a flash off this object 1.2 seconds before observing a flash off Io. Therefore, if this were the same event as seen by Raghavan, we should have seen it in the previous image and not the one concurrent with her observation. We now think these bright pixels are due to a cosmic ray.

It seems unlikely that what we have seen here is a real flash. Both possible flash observations can easily be accounted for by noise. They do occur 2 minutes 48 seconds before the plume from impact E was observed from Calar Alto (*Herbst and Hamilton*, 1995) which is consistent with the timing of a precursor flash as seen for other impacts. E was observed during the daytime at Calar Alto, so they were not able to record a precursor event to which we could compare our times.

If we use the kinetic energy/luminosity relation discussed in the previous section, we obtain an ablated mass of 1.6×10^{16} g. This is somewhat high for a comet fragment, since we would expect that a 1 km radius comet would only have a mass of about 10^{15} g. It seems the evidence is simply not strong enough to declare this to be a flash.

5. Results from Impact K

We obtained both photometry and CCD images covering the time of impact K. The photometric data for this event are similar in quality to the data for E. It contains many saturations due to scattered light from Jupiter entering the aperture. So to look for evidence of a flash we would need to have an event time from a separate observation. The CCD images provide the best chance to find a flash. With an exposure time of 2.43 seconds and dead time (for readout) of 1.83 seconds, we should have observed the flash if it occurred. We used a filter with a bandpass of $\sim 570 - 670$ nm.

We have done aperture photometry on the position of Europa in the images within five minutes of the accepted impact time of 10:24:14 ± 30 sec UT [*Chodas*, SL-9 Bulletin Board]. In addition to the limb, and the position of the eclipsed Europa, each image contains Io. This allows us to accurately find the position of Europa in the images by first centroiding on Io and then using the ephemeris and the known orientation of the CCD on the sky to offset to Europa's position. We performed photometry on the position of Europa, and obtained the lightcurve shown in Fig. 6.

Comparison of the current background subtracted fluxes for the Europa region reveals no obvious flashes. Therefore, we can use the average value of the measured Europa region to obtain an upper limit for the flash. This calculation must be done slightly differently than for D and E since there is not a solar component with which to compare. Using Io as a reference we turned the average value of the Europa region into a magnitude. To find the apparent magnitude of Io in our bandpass we first applied the Morrison and Morrison solar phase correction to the V magnitude of Io at a solar phase of 6 degrees to obtain the V magnitude of Io at a solar phase of 10.7 degrees, the solar phase at the time of the observations. Then, using the Io reflectivity spectrum of McFadden *et al.* (1980) we scaled the V magnitude of Io to the magnitude in our bandpass, resulting in $m_{Io} = 5.03$. This allows us to convert the measurement of Europa in eclipse from an instrumental magnitude to a true magnitude of $m_{Europa} = 19.8$. To turn this into a flux we use the flux of the Sun integrated over our bandpass and scaled to the distance of Europa:

$$m_{\odot} - m_{Europa} = -2.5 \log(\frac{F_{\odot}}{F_{Europa}}),$$

where $m_{\odot}$ is the magnitude of the Sun and $F_{\odot}$ is the solar flux. Both of these quantities are scaled to 5.16 AU, the distance of Europa from Earth. F_{Europa} is the flux from Europa as measured at Earth. The measured luminosity is then $F_{Europa} \cdot 4\pi d^2_{Europa,Earth}$, where $d_{Europa,Earth}$ is the distance between Europa and the Earth.

To convert the measured luminosity to the luminosity of the flash on Jupiter, we set it equal to the luminosity from the flash reflected from Europa. $L_{flash} \cdot \pi r^2_{Europa}/2\pi d^2_{Europa,impact}$ is the power from the flash received by Europa, where L_{flash} is the luminosity of the flash on Jupiter, r_{Europa} is the radius of Europa, and $d_{Europa,impact}$ is the distance between Europa and the impact point. The reflected portion of this power is reduced by the Albedo of Europa and the impact phase function. Therefore the luminosity of the flash which is reflected from Europa is

$$L_{flash} \cdot \frac{\pi r^2_{Europa}}{2\pi d^2_{Europa,impact}} \cdot Albedo \cdot P(\beta).$$

The luminosity of the flash on Jupiter at 620 nm (the average wavelength of our bandpass) is then:

$$L_{flash} = \frac{F_{Europa} \cdot 2\pi d^2_{Europa,impact}}{\pi r^2_{Europa} \cdot Albedo \cdot P(\beta)} \cdot 4\pi d^2_{Europa,Earth}$$

At the time of the impact of fragment K, $\beta = 4.2°$, $d_{Europa,impact} = 6.5 \times 10^5$ km, and $d_{Europa,Earth} = 7.7 \times 10^8$ km. $Q = 0.757$ (*Lumme and Bowell*, 1981b), so $P(\beta) = 0.92$. This yields a two sigma upper limit for the luminosity of the impact flash for fragment K of 2.6×10^{21} erg sec^{-1} nm^{-1} at 620 nm.

Galileo observed a peak luminosity for the impact of K of 5.7×10^{19} erg sec^{-1} nm^{-1} with the SSI camera at 890 nm. Assuming a 8000 K blackbody, this is 1.3×10^{20} erg sec^{-1} nm^{-1} at 620 nm. The linear fit gives a similar value of 1.0×10^{20} erg sec^{-1} nm^{-1}, only a factor of 20 lower than our upper limit.

Now if we turn to our mass/luminosity relation and use $\beta = 0.009$, and a flash duration of 5 seconds, we find an upper limit on the ablated mass of the K fragment of 8×10^{12} g. If a few to ten percent of the fragment was ablated during the meteor phase, it is possible that the two consistently bright points in the lightcurve just before Impact time represent an actual detection of a flash (Fig. 6).

6. Precursor Timing

Our possible detection of the first precursor event from impact D occurred only 26 seconds before the second precursor, half the time separating the well observed precursor events from the large fragments. It would seem that our first precursor has occurred at the wrong time to be a real event. However, there is evidence to suggest that there is a correlation between impactor size and time between the first and second precursors. A plot of fragment brightness *vs.* precursor separation time shows a trend of the precursors actually occurring closer together in time with smaller fragment sizes (Fig. 7). The smaller impactors penetrate less deeply into the atmosphere, and thus it takes less time after the initial bolide flash for the plume to rise above the limb.

The strongest evidence for this hypothesis is in the precursor for impact C. Though it was originally reported by Takeuchi et al. (1995) as a single precursor event, close inspection of the precursor lightcurve reveals that there are actually two peaks 35 seconds apart (Fig. 8). Though the absolute flux of this lightcurve may be too low by as much as a factor of two, due to calibration uncertainties, the relative flux is precise to within a few percent.

Since fragment D was one of the smallest fragments for which a lightcurve was observed, it would be reasonable to expect that its precursor events occurred even more closely together in time than those for fragment C. Therefore the timing does not rule out our detection as a possible precursor flash.

7. Conclusions

We can not conclusively say whether or not we observed any reflections off the satellites of the impact flashes from Shoemaker-Levy 9's collision with Jupiter. There are several tantalizing possibilities, but none of the observations are far enough out of the noise to be able to say what they are with certainty.

We can say however, that we see evidence for decreasing time between the two precursors with decreasing fragment size. A probable physical explanation of this is that the smaller fragments broke up higher in the atmosphere than the larger fragments. The rising fireball then had less distance to travel to appear beyond the limb of the planet, and was seen closer in time to the bolide entry. Modelling is required to test this theory, but is beyond the scope of this paper.

Of all our observations, the D flash is most likely to be real. There are no observations of other possible flashes, but compared to the onset times of the one observed precursor and the main event, it is reasonable to think that our flash may have occurred near the time of the unobserved first precursor. This flash also has the most convincing lightcurve. However, our observed luminosity is several orders of magnitude brighter than anything Galileo observed. Line emission could explain this discrepancy; however, if this is the case, then a large fraction of the fragment was ablated during the meteor phase.

It seems highly unlikely that what was observed close to the time of impact of fragment E was a real flash. On its own, it is hard to believe our data contain anything other than scattered light from Jupiter. However, that particular saturation does occur at the same time as a potential flash seen from India. The luminosity of this flash however, is even brighter than that of D, so the discrepancy between our data and the Galileo observations is larger, and Ca and Mg lines are less able to explain the observed luminosity. We did expect an E flash to be brighter than D (Fig. 2), but not by almost two orders of magnitude.

Impact K should have been our best chance to observe a flash. This was the only impact to occur while a satellite was in eclipse, so there was no reflected sunlight to overwhelm the lower intensity flash. However there is little evidence of a flash. There are two consecutive images of similar brightness, near the impact time which could possibly be a two sigma detection. If this was due to line emission from the bolide entry then approximately one to ten percent of the mass of the fragment would have been ablated during the meteor phase.

Overall, the spectra of the impact events were very different than predicted. The luminosities that Galileo observed indicate that detection of flashes due to blackbody radiation would not have been possible at visible wavelengths, except perhaps for impact K. However, reflected line emission from meteor ablation may explain our tentative detections.

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References

A'Hearn, M. F., R. Meier, D. Wellnitz, L. Woodney, R. Martin, T. Smith, and A. Verveer 1995. Were Any Impact Flashes Seen in Reflection from the Satellites?. In *European SL-9/Jupiter Workshop, Garching, 13-15 February 1995* (R.M. West and H. Boehnhardt, eds.), pp. 113-118. European Southern Observatory Conference and Workshop Proceedings no. 52, Garching.

Birch, P. 1994. Private communication.

Bronshten, V. A. 1983. *Physics of Meteoric Phenomena.* D. Reidel Pub. Co., Boston.

Carlson, R. W., P. Drossart, T. Encrenaz, P. R. Wissman, J. Hui, and M. Segura 1997. Temperature, Size and Energy of the Shoemaker-Levy 9 G-Impact Fireball., *Icarus*, **128**, 251-274.

Chapman, C. R., W. J. Merline, K. Klaasen, T. V. Johnson, C. Heffernan, M. J. S. Belton, A. P. Ingersoll, and the Galileo Imaging Team 1995. Preliminary results of Galileo direct imaging of SL-9 impacts., *Geophys. Res. Lett.*, **22**, # 12, 1561-1564.

Chodas, P. and D. K. Yoemans 1996. The orbital motion and impact circumstances of Comet Shoemaker-Levy 9. In *The Collision of Comet Shoemaker-Levy 9 and Jupiter*, pp. 1-30. Cambridge University Press, Cambridge.

Consolmagno, G. and G. Menard 1995. A search for variations in the light curves of Io and

Europa during the impact of Comet SL9: A, H, and Q events., *Geophys. Res. Lett.*, **22**, # 12, 1633-1636.

Costa, R. D. D., J. A. de Freitas Pacheco, P. D. Singh, A. A. de Almeida, and S. J. Codina-Landaberry 1997. Atomic Emission in the Spectrum Observed After the Impact Between the L-Fragment of Comet D/Shoemaker-Levy 9 and Jupiter., *Astrophys. J.*, **485**, 380-382.

Friichtenicht, J. F., and D. G. Becker 1973. Determination of Meteor Parameters Using Laboratory Simulation Techniques. In *Evolutionary and Physical Properties of Meteoroids*, pp. 53-81. NASA SP-319.

Halliday, I., A. A. Griffin and A. T. Blackwell 1981. The Innisfree Meteorite Fall: A Photographic analysis of Fragmentation, Dynamics and Luminosity., *Meteoritics*, **16**, 153-170.

Halliday, I. 1987. The spectra of meteors from Halley's comet, *Astron. Astrophys.*, **187**, 921-924.

Hamilton, D. P., T. M. Herbst, A. Richichi, H. Bohnhardt, and J. L. Ortiz 1995. Calar Alto observations of Shoemaker Levy 9: Characteristics of the H and L impacts., *Geophys. Res. Lett.*, **22**, # 17, 2417-2420.

Hammel, H. B. and 16 colleagues 1995. HST imaging of Atmospheric Phenomena Created by the Impact of comet Shoemaker-Levy 9., *Science*, **267**, 1288-1296.

Herbst, T. M., D. P. Hamilton, H. Bohnhardt, and J. L. Ortiz-Moreno 1995. Near infrared imaging and spectroscopy of the SL-9 impacts from Calar Alto., *Geophys. Res. Lett.*, **22**, # 17, 2413-2416..

Labs, D., H. Neckel, P. C. Simon, and G. Thuiller 1987. Ultraviolet Solar Irradiance Measurement from 200 to 358 nm During Spacelab 1 Mission., *Solar Phys.*, **107**, 203-219..

Lumme, Kari and Edward Bowell, 1981a. Radiative Transfer in the Surfaces of Atmosphereless Bodies I. Theory., *Astron. J.*, **86**, 1694-1704.

Lumme, Kari and Edward Bowell, 1981b. Radiative Transfer in the Surfaces of Atmosphere-less Bodies II. Interpretation of the Phase Curves., *Astron. J.*, **86**, 1705-1721.

Martin, T. Z., G. S. Orton, L. D. Travis, L. K. Tamppari, and I. Claypool 1995. Observation of Shoemaker-Levy Impacts by the Galileo Photopolarimeter Radiometer., *Science*, **268**, 1875-1878.

McFadden, L. A., *et al* 1980. Visible Spectral Reflectance Measurements (0.33 – 1.1 μm) of the Galilean Satellites at Many Orbital Phase Angles., *Icarus*, **44**, 410-430.

McGregor, P. J., P. D. Nicholson, and M. G. Allen 1996. CASPIR Observations of the Collision of Comet Shoemaker-Levy 9 with Jupiter., *Icarus*, **121**, 361-388.

Meadows, V., D. Crisp, G. Orten, T. Brooke 1995. AAT IRIS Observations of the SL-9 Impacts and Initial Fireball Evolution. In *European SL-9/Jupiter Workshop, Garching, 13-15 February 1995* (R.M. West and H. Boehnhardt eds.), pp. 129-134. European Southern Observatory Conference and Workshop Proceedings no. 52, Garching.

Morrison, D. and N. D. Morrison 1977. Photometry of the Galilean Satellites. In *Planetary Satellites.* (Joseph A. Burns Ed.), 363-378. The University of Arizona Press, Tucson.

Neckel, H. and D. Labs 1984. The Solar Radiation Between 3300 and 12500 Å., *Solar Phys.*, **90**, 205-258.

Nicholson, P. D., P. J. Gierasch, T. L. Hayward, C. A. McGhee, J. E. Moersch, S. W. Squyres, J. Van Clebe, K. Matthews, G. Neugebaur, D. Shupe, A. Weinberger, J. W. Miles and B. J. Conrath 1995. Palomar observations of the R Impact of Comet Shoemaker-Levy 9: Light Curves., *Geophys. Res. Lett.*, **22**, #12, 1613-1616.

Noll, K. S., M. A. McGrath, L. M. Trafton, S. K. Atreya, J. J. Caldwell, H. A. Weaver, R.

V. Yelle, C. Barnet, and S. Edgington 1995. HST Spectroscopic Observations of Jupiter After the Collision of Comet Shoemaker-Levy 9., *Science*, **267**, 1307-1313.

Raghavan, N. (1997), private communication.

Sekanina, Z. 1993. Disintegration Phenomena Expected During Collision of Comet Shoemaker-Levy 9 with Jupiter., *Science*, **262**, 382-387.

Takeuchi, Satoru, Hitoshi Hasegawa, Jun-ichi Watanabe, Takuya Yamashita, Masanao Abe, Yuka Hirota, Eiji Nishihara, Shi-ichiro Okumura, and Atsushi Mori 1995. Near-IR imaging observations of the cometary impact into Jupiter., *Geophys. Res. Lett.*, **22**, 1581-1584.

Weaver, H. A., and 20 colleagues 1995. The Hubble Space Telescope (HST) Observing Campaign on Comet Shoemaker-Levy 9., *Science*, **267**, 1282-1287.

Woodney, L. M., R. Meier, M. F. A'Hearn, D. Wellnitz, and T. Smith 1994. High-Speed Photometry of the Jovian Satellites During Comet P/Shoemaker-Levy 9's Impact with Jupiter. *Bull. Am. Astron. Soc.* **26**, 1572.

Zahnle, K. and M.-M. Maclow 1995. A simple model for the light curve generated by a Shoemaker-Levy 9 impact., *J. Geophys. Res.*, **100, # E8**, 16885-16894.

Table I. Observations

Impact	Date	Start	Stop	What was observed
CCD Imaging				
D	July 17	11:16:02	12:07:13	Io and Europa
E	July 17	14:53:51	15:40:59	Impact Limb
K	July 19	10:02:13	10:33:00	Io, Eclipsed Europa, Impact Limb
N	July 20	10:06:27	12:18:40	Impact Limb
P2	July 20	15:05:55	15:26:09	Jupiter
Photometry				
D	July 17	11:30	12:00	Io
E	July 17	14:56	15:26	Io
K	July 19	10:07	11:10	Eclipsed Europa

Table II. Flash
Comparison of Measured Luminosity to Model Luminosities and Ablated Masses

Impact	λ (nm)	Measured[a] Peak	Predictions from Galileo Data[a,b] Blackbody Fit	Linear Fit	Ablated Mass[c] (kg)
D	422	4.6×10^{23}			5.6×10^{14}
N	422		6.4×10^{19}	1.1×10^{20}	
E	422	1.1×10^{25}			1.6×10^{16}
H	422		3.0×10^{20}	1.6×10^{20}	
K	620	2.6×10^{21}	1.3×10^{20}	1.0×10^{20}	8.0×10^{12}

a All luminosities in erg $\sec^{-1}$ nm^{-1}.

b Galileo data has been converted from original wavelength to our data's wavelength, using the listed models.

c Masses derived from meteor ablation model described in text.

Figure Captions

Fig. 1 Photometry of Io near the time of the impact of fragment E. These two minutes of data are typical of our observations for E. High winds prevented us from recording a steady lightcurve of Io. Low points in the lightcurve are due to tracking errors. They can be due to loss of Io from the aperture, or saturation from Jovian scattered light since saturation of the voltage to frequency converter results in low values. The inset shows the saturated lightcurve at the time of Raghavan's reported flash.

Fig. 2 Impact luminosity *vs.* fragment brightness. Open symbols represent the peak luminosities (erg $\sec^{-1}$ nm^{-1}). These values have been multiplied by a factor of ten in the plot so that they may be more easily compared to the integrated luminosities (erg nm^{-1}) which are represented by filled symbols. Circles represent the SSI observations which were corrected to 945 nm while triangles represent the PPR observations at 945 nm. The dashed line represents a slope of one, while the solid line is a slope of 3/2. These represent the proportionality we would expect to see between the luminosity and the cross section of the nucleus and the luminosity and the mass respectively. Fragment brightness are in arbitrary units derived from HST observations (Weaver *et al.*, 1995).

Fig. 3 Impact site classification *vs.* fragment brightness. Fragment brightness is as in Fig. 2, and site classification is from Hammel *et al.*, 1995. There is clearly a relation between impact spot size and fragment brightness, albeit with some scatter. Since there is also a correlation between spot size and luminosity of the impact, this figure can be combined with Fig. 2 to estimate what the luminosity of impacts not observed by Galileo was.

Fig. 4 The observing geometry. α is the solar phase angle and β is the impact phase angle. This figure is not to scale. The solar phase angle α is virtually the same at both Io and Jupiter.

Fig. 5 Lightcurve of fragment D as measured with the photometer. The small rise starting at 11:54:20 UT is distinct from other noise of the same amplitude in that it is a trend over several seconds. In the top figure the data have been integrated over 0.1 second intervals. The lower plot shows the data at the resolution at which we digitized it (100 samples per second).

Fig. 6 Lightcurve of Europa during the K impact, measured with the CCD in red light. There is no clear evidence of a flash. However, the two points of the same brightness in the lightcurve, just before impact time, have both a physically plausible luminosity and are consistent in time with the precursors observed by McGregor *et al.*, 1996.

Fig. 7 A plot of the time between the two precursors peaks in seconds *vs.* fragment brightness shows a correlation. The smaller fragments penetrated less deeply, and thus the plume took less time to rise above the limb. Precursor timing data from D, C : this work, R: Nicholson *et al.*, 1995, H,L: Hamilton *et al.*, 1995, K: Takeuchi *et al.*, 1995, G1: McGregor *et al.*, 1996.

Fig. 8 The C precursor as observed by Takeuchi et al. (1995), shows two peaks. Both precursors, marked by the arrows as PC1 and PC2, have been resolved, and they occurred 35 seconds apart.