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The Fragment R Collision: W. M. Keck Telescope Observations of SL9

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The W. M. Keck telescope was used to observe the impact of comet Shoemaker-Levy 9 (SL9) fragment R at a wavelength of 2.3 micrometers on 21 July 1994. The data showed three outbursts. The first flash lasted about 40 seconds and was followed 1 minute after its peak by a second flash that lasted about 3 minutes. A third, longer lasting flare began 6 minutes after the first flash and lasted for 10 minutes. At its maximum brightness, the flare outshone Jupiter. The two short flashes are probably associated with the initial meteor trail and the subsequent fireball, respectively. The bright flare occurred when the impact site rotated into view. These data show that the explosion ejected material at least 1300 kilometers above the visible cloud tops. The luminosity of the impact site during the long bright flare was probably maintained by the release of gravitational potential energy, as this material fell back onto the lower atmosphere.

On 16 July 1994, the first fragment of comet Shoemaker-Levy 9 (SL9), fragment A, crashed into Jupiter, soon followed by fragments B through W. The observations presented here, which consist of a sequence of infrared images every 7.7 s, show the impact of fragment R and its immediate consequences. The observed response of Jupiter's atmosphere constrains the impact energetics and kinematics and provides a direct test of impact theory.

The 10-m W. M. Keck telescope (*1*) at Mauna Kea, Hawaii, was used to observe the impact of SL9 fragment R. The data were obtained with the facility near-infrared camera (*2*). The camera is equipped with a Santa Barbara Research Corporation InSb array (256 pixels by 256 pixels) and has a pixel size of 0.15 arc sec. We observed Jupiter with a narrow-band filter centered at a wavelength of 2.3 μm (wavelength, 2.28 to 2.31 μm). The planet is very dark at this wavelength, because sunlight is absorbed at 2.3 μm by CH_4 above Jupiter's cloud layers and only material at high altitudes, such as the high-altitude haze layers present above Jupiter's poles, stand out as bright features.

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Image Sequences: Moviemaking

We used the light-gathering power of the Keck telescope to obtain a record of the R event with many frames per minute. Data were taken in a movie mode, which yields one frame every 7.743 s, each with a total integration time of 4.347 s (*3*). The relative time of each frame is determined with reference to the quartz-controlled clock in the real-time system that controls the camera. The 1σ uncertainty in relative times is <10 ms. The real-time clock was synchronized to the observatory WWV and Global Positioning Satellite clocks. The systematic error in the absolute time is <0.5 s.

Three movie sequences were obtained, starting approximately 21 min before the expected fragment R impact [05:29 universal time (UT) (*4*)]. The first sequence runs from 05:08 to 05:18 UT, the second from 05:18 to 05:36 UT, and the third from 05:36 to 05:57 UT. There is a gap of a few seconds between each movie. Another sequence could not be obtained because the telescope was threatened by fog.

The movie shows two faint flashes on the limb at a latitude of $\approx -44°$ (Fig. 1, panels 2 through 5) followed by a dramatic bright flare (Fig. 1, panels 7 and 8). The two flashes appeared as bright points on the limb in projection against the old G-D impact site complex. The end of the movie recorded the new R impact site rotating into view.

The first flash (Fig. 1, panel 2) was first seen at 05:34:44.5 UT (Table 1). In the next frame of the movie, the flash reached its peak, after which it decayed. The first flash was clearly visible only in five frames, or for 40 s. The rise time of the flash was ≈15 s, and the decline was slower, with an *e* folding time of ≈30 s. One minute later, a second flash occurred (Fig. 1, panel 4). This flash was also caught on the rise, but its decay was much slower with an *e* folding time of ≈180 s. Emission was visible for at least 180 s (Fig. 1, panels 5 and 6), when a third brightening occurred. There is some evidence for a brief brightening at the end of the second flash.

Almost immediately after the second flash faded, at about the expected time for the impact site to rotate into view (*4*), a new feature appeared on the limb (Fig. 1, panel 7). The new R impact site soon outshone the rest of the planet at this wavelength. The bright flare reached its maximum intensity (Fig. 1, panel 8) approximately 4 min after it became visible. Ten minutes after its first appearance, the intensity dropped to the level of that of the old G-D impact sites. As the bright flare faded and its emission returned to a level comparable to that of the G-D impact sites, a distinct change in the morphology of the emission region occurred (Fig. 1, panel 9). Up until this point the region was unresolved, but in the final 10 min of the movie the impact site was clearly resolved in a direction tangential to the limb with a length of ≈2 arc sec. Thus, in an interval of ≈1000 s, the impact had influenced a region of ≈7500 km. The lateral extent appeared to increase slightly until the final fading began. The D-G complex had moved off the limb by this stage, and the new impact site was clearly resolved from previous impact sites.

Figure 2A shows the 2.3-μm light curve of the R impact (*5*). The detector began to saturate when the brightness at 2.3 μm exceeded a magnitude of 3.3 [equivalent to 30 janskys (Jy), a unit of flux density, where 1 Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}]. However, when the core of a stellar image is saturated there are still many unsaturated pixels in the wings of the point spread function. Photometry was recovered from saturated images by extrapolation of the flux measured in an unsaturated annular aperture with the use of the photometric curve of growth. We checked the reliability of this procedure by measuring the curve of growth before and after the fragment R event to ensure that it had not changed. Consequently, we can state with confidence that the flickering at the peak of the bright flare (Fig. 2A) is not an artifact.

The absolute scale of the photometry

was established relative to the standard GJ 811.1 (where the K magnitude is 6.93). The color term between the K magnitude and the 2.3-μm wavelength was ignored because GJ 811.1 is a M3V star with a CO absorption index with a magnitude of only 0.013 (6). The magnitude of the systematic error in the calibration is ≈0.1. Although the weather was not clear before sunset, inspection of the sky suggested that conditions were photometric during the fragment R event. This was confirmed by photometry of the L and K impact sites, which show only a small, slow secular variation that is a result of the rotation of Jupiter.

The aperture includes part of the G-D impact sites, so the photometry includes emission from them. Consequently, the light curve shows a slowly rising contribution as they rotate into view. By the end of the observations, the emission from the R and G-D impacts was spatially resolved, and the G-D complex fell out of the aperture. This accounts for the drop in flux that began at 05:55 UT. Figure 2B shows a detail of the light curve that includes the first two flashes. A smooth base line has been subtracted to remove the contribution of the old impact sites. We have not attempted a similar subtraction for the bright flare. For most of its duration, the bright flare dominated the old impact sites, and a correction is unnecessary, whereas at the end of the movie, there is an insufficient base line to make an accurate subtraction.

We can integrate the 2.3-μm light curve in an attempt to determine the total energy radiated by the R event. There are several problems with such an estimate: (i) the observations are at only one wavelength; (ii) the impact site was initially occulted by Jupiter; and (iii) the explosion probably occurred at or below 1 bar, where the absorption optical depth at a wavelength of 2.3 μm ($\tau_{2.3\ \mu m}$) ≈ 100. Radiation at a wavelength of 2.3 μm can escape when hot gas has risen up to a pressure of ≈0.01 bar, where $\tau_{2.3\ \mu m}$ ≈ 1. The bolide may also have left a tunnel of hot, dissociated atmospheric gases, in which case there is an optically thin path for 2.3-μm radiation to escape. Even when the impact site was still behind the limb, we expected to see radiation if the fireball reached a high enough altitude. For an impact site that is 4.8° behind the limb (4), material at a height of ≈240 km above the 1 bar level will be visible. Consequently, if we integrate the area under the light curve we obtain a lower limit to the amount of energy released during the fragment R event.

Assuming that the detected radiation is thermal emission, then for a given frequency ν, the temperature that minimizes the inferred luminosity occurs when $h\nu/kT = 3.921$, where h is Planck's constant and k is Boltzmann's constant. For a wavelength of 2.3 μm, the minimum occurs for $T = 1600$ K. Assuming this temperature and integrating the entire light curve yields $E = 3.0 \times$

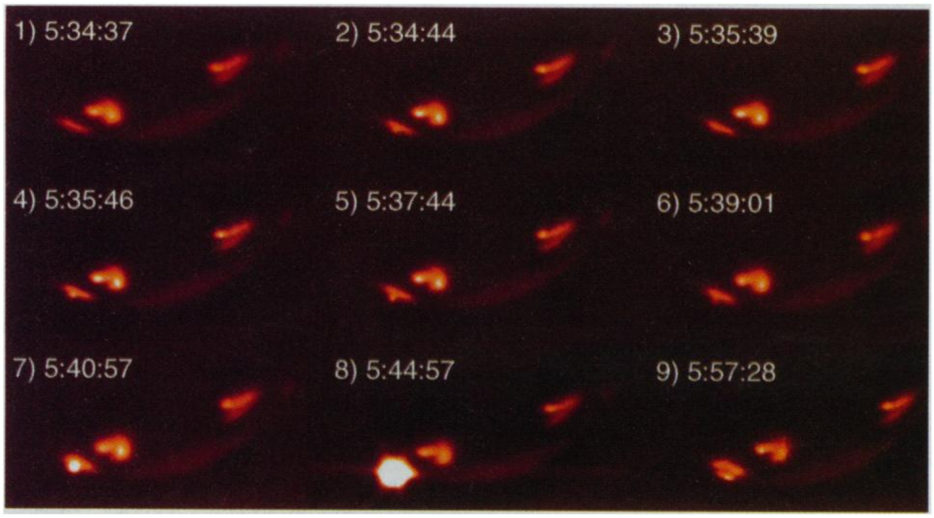

Fig. 1. Each of the nine panels is a frame selected from the movie of the fragment R event showing two precursor flashes and a bright flare. The time increases from left to right, top to bottom. Each panel is labeled with the universal time. North is at the top, and east to the left. The field of view is 38 arc sec by 19 arc sec. Jupiter's spin axis is at a position angle of 20°. The wavelength of observation is 2.3 μm. In panel 1, only the high-altitude hazes above Jupiter's south pole and former impact sites stand out as bright features. The south polar region is visible as a faint arc in the lower part of the frame. The old impact sites of fragments L and K are the bright spots east and west of the meridian, respectively. The G-D impact site has just rotated into view on the eastern limb, whereas impact site C is disappearing in the west.

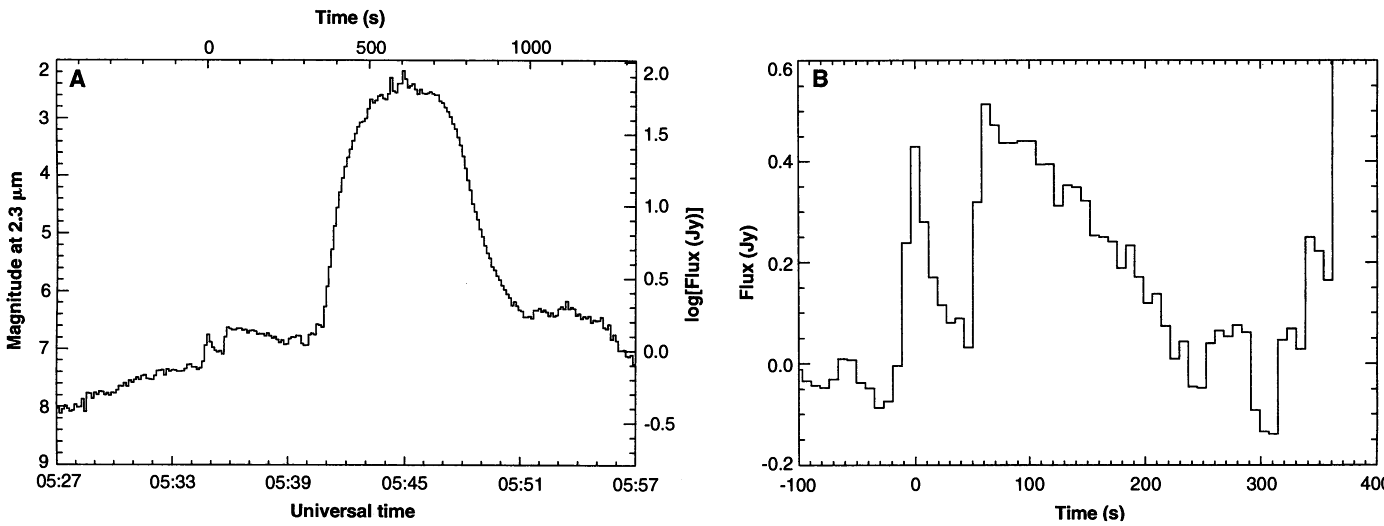

Fig. 2. (**A**) Light curve of the R event. Universal time is plotted against the 2.3-μm magnitude. The top of the plot is labeled in seconds from the peak of the first flash, and the right axis shows the flux on a log scale. The slow rise at the start of the movie is a result of the G-D impact site, which was on the limb and rotated into view. (**B**) A section of the light curve shown in (A) in the vicinity of the two precursor flashes. Time is measured in seconds from the peak of the first flash.

10^{24} ergs. This is, as expected, a small fraction of the expected explosion energy. The kinetic energy of a sphere of density 1 g cm^{-3} half a kilometer in diameter [probably characteristic of fragment R (*7–9*)] and traveling at 60 km s^{-1} is 1×10^{27} ergs. Appropriate black-body temperatures may be as high as ≈5000 K or as low as ≈800 K (*10–12*), in which case E would be larger by a factor of 5, so that $E = 1.5 \times 10^{25}$ ergs, implying that the radiative efficiency may be as high as 0.01.

It is unlikely that a substantial fraction of the 2.3-μm emission is attributable to scattered sunlight. At its peak brightness, the flux from the impact site is ≈65 Jy. An area with a diameter of 12,000 km with unit reflectivity would be necessary to provide this flux. Such a region would subtend a diameter of ≈3.2 arc sec. The images of the flashes have a full width at half maximum of ≤1 arc sec (except at the very end of the movie). Because there is no star in the images from which we can estimate the point spread function, we take 1 arc sec as an upper limit on the emitting region.

Atmospheric Phenomena

The initial passage of the comet through Jupiter's atmosphere formed a bow shock, leaving a meteor trail. If the comet maintained its integrity, it could penetrate deeply into the atmosphere. If it broke up or was ablated, then it would not reach as deeply and the energy deposition would be localized, causing an explosion that ejects atmospheric gases, forming a fireball or plume above the explosion site (*10–15*). Finally, the ejecta would fall back down onto the lower atmosphere where it would shock and dissipate its gravitational potential energy (*16*). These major events are recorded in the Keck light curve of the R event. Here, we argue that: (i) the first flash is due to the meteor trail; (ii) the second flash is the fireball rising above the jovian horizon; and (iii) the bright flare coincides with the rotation of the new impact site onto the limb.

The two flashes and the bright flare all fell within the 95% confidence interval of the predicted impact time derived from astrometry (*4*), and therefore the impact event cannot be unambiguously identified on this basis. However, the predicted impact site for R is 4.8 ± 0.33° behind the limb (*4*), which implies that the impact occurred 470 ± 30 s before the impact site rotated onto the limb. The slow rise in brightness of the new impact site, as it rotated into view, indicates that the emitting region was extended. Therefore, we can figure the time of the impact from the midpoint of the rising branch of the bright flare. This places the impact time at 05:34:40 UT with an uncertainty of 30 s. There is thus strong evidence for associating the first flash with atmospheric entry because of the close coincidence in time between the first flash (observed at 05:34:52 UT) and the inferred impact.

The comet traveled several hundred kilometers through Jupiter's atmosphere before it slowed down and exploded (*10, 12, 14*). Energy was lost at the rate at which work is done by drag forces. Before the comet fragment was slowed substantially, this is (in ergs per second)

$$\frac{dE}{dt} = 5.8 \times 10^{21}\, \rho_a r_c^2$$

(where ρ_a is the atmospheric density in units of 10^{-9} g cm^{-3} and r_c is the comet radius in kilometers) for v = 60 km s^{-1} (*11, 12, 14*), which produced a meteor trail high above the stratosphere. We can calculate the altitude of the meteor trail assuming that it radiates efficiently. The peak flux of the first flash was about 0.4 Jy, corresponding to 5×10^{19} erg s^{-1}, which implies that the meteor trail is formed at $\rho_a \approx 10^{-10}$ g cm^{-3} for a fragment of radius r_c = 0.25 km. Thus, the meteor trail was visible from Earth because this density corresponds to 14 scale heights, or about 400 km, above the 1-bar level.

The meteor trail disappeared behind the limb at an altitude of 240 km; therefore, the trail should have lasted for about 4 s. Scattering by dust may have provided an indirect way to continue to see the meteor trail once the comet dropped out of view behind the limb. Dust from the coma is ruled out because the first flash was unresolved (<1 arc sec) while the coma extended over a few seconds of arc (*7*). A more likely source of dust is freshly ablated material from the comet.

The largest comet fragments are expected to penetrate no more than 300 km below 1 bar of atmospheric pressure (*10, 13, 14*). Thus, even with dust scattering the total duration of the meteor can be no more than about 16 s. The first flash was visible for much longer than this. The length of the first flash may be explained if fragment R was broken up into a chain of nuclei by Jupiter's strong tidal forces; a duration of 30 s suggests a string of fragments about 1800 km long.

The amplitude of the first and second flashes was similar, but the decay time of the second was about 6 times longer than that of the first, which suggests that each is caused by a different phenomenon. If the first flash was the entry flash, then the second flash must have resulted from the fireball. The interval of about 60 s between the entry flash and the second flash is consistent with this conclusion.

Numerical simulations suggest that the comet fragment leaves a cylinder of hot, high-pressure gas. This creates a fireball and associated shock that expand most rapidly back up the entry trajectory, ballistically ejecting a mass of atmosphere. Hot debris ejected by the explosion is expected to rise into view above the jovian horizon on a time scale of 10^2 s (*10–13, 15*). Thus, the observed 60-s delay between the entry flash and second flash is highly suggestive of the appearance of the fireball over Jupiter's limb. An interval of 54 s between the peak of the first flash and the first beginning of the second flash implies that the fireball, on a ballistic trajectory with an initial vertical velocity of 8 km s^{-1}, had risen 395 km. At the time the fireball appeared, the Earth line of sight was 190 km above the 1-bar level, placing the explosion site at a depth of about 200 km. This is the maximum possible depth, because we have neglected the time required for the comet to explode and to accelerate the ejecta. Different researchers disagree on penetration depths, and comparison with the results of numerical simulations variously suggests that this value corresponds to the explosion of an ice sphere somewhat less than 1 km (*10*) in

Table 1. Impact R time line.

Universal time, 21 July 1994*	t (s)†	Event
05:08:11.7	−1592.8	Start of first movie sequence
05:18:01.5	−1003.0	End of first movie
05:18:21.1	−983.4	Start of second movie
05:28:50 ± 6:12	−354.5 ± 372	Predicted impact time (*4*)
05:34:44.5	0.0	First flash
05:34:52.2	7.7	Peak of first flash
05:35:46.4	61.9	Second flash
05:35:54.1	69.6	Peak of second flash
05:36:09.6	85.1	End of second movie
05:36:33.9	109.4	Start of third movie
05:40:57.2	372.7	Bright flare begins
05:44:57.2	612.7	Peak of bright flare
05:51	976	R impact site faded to G-D level
05:57:28.3	1363.8	End of third movie

*All times refer to the middle of each exposure. The exposure time of each frame is 4.34 s, and the interval between frames is 7.73 s. †Time from the start of the first flash.

diameter, perhaps even up to 2 km (*10, 12–14, 17*).

Zahnle and MacLow (*16*) calculate the luminosity from the part of the fireball above the limb of Jupiter that is visible from Earth. When E is 1×10^{27} ergs and the impact site is 4° behind the limb, the predicted luminosity from hot gas ($T \approx 2000$ K) visible above the limb reaches a peak of 6×10^{20} erg s^{-1} 45 s after the explosion, after which the flux decays with an e folding time of $\approx$7 s. The predicted peak flux at Earth, assuming that the fireball radiates like a black body, is greater by a factor of $\approx$4, and the e folding decay time is $\approx$25 times faster than observed. The qualitative similarity of this value to the observed behavior is encouraging, and the neglect of opacity sources, apart from H^-, may explain why the calculated fireball temperature dropped too quickly to be consistent with the observed slow decay of the second flash.

The appearance of Jupiter's limb at the end of the movie (Fig. 1, frame 9) indicates that the bright flare was a result of the impact site rotating into view. The slow rise of the flare may indicate that the emitting region was extended, in which case the 150-s rise time indicated a size of about 1300 km. By the end of the movie (15 min after the first flash), the new impact site was resolved and had a size of $\approx$2 arc sec or 7500 km. This indicates that the impact site was expanding rapidly. Images of old impact sites (Fig. 1) show that the expansion was not symmetric but mostly in one direction; therefore, we estimate the expansion velocity as 7500 km/1000 s = 8 km s^{-1}. The large extent of the impact site must have been a result of the lateral growth of the fireball high above the location of the explosion, because the lateral expansion of the shock as a result of an explosion in an exponential atmosphere is limited to a diameter of $\approx 7h$ (*18*) (with atmospheric scale height $h \approx 30$ km) at the point of the explosion. If the vertical component of the gas velocity is comparable to the lateral expansion speed of $v \approx 8$ km s^{-1}, then gas on a ballistic trajectory reaches an altitude of $z = v^2/(2g) = 1280\ (v/8 \text{ km s}^{-1})^2$ km, where v is the initial upward velocity and g is the local gravitational acceleration. This is consistent with our previous conclusion that the fireball achieves a high enough altitude to account for the second flash. Because the expansion is directed upward by the atmospheric density gradient, we may have underestimated our value for v, and 1280 km is a lower limit.

The decay of emission from the fireball (the second flash) probably corresponds to the phase of rapid adiabatic cooling as it rose above the jovian horizon. Hence, the intensity and duration of the final flare was surprising because extrapolation of the second flash's light curve would suggest that the fireball made a negligible contribution to the luminosity of the explosion site by the time it had rotated into view. However, at this late stage, material from the fireball began to rain back down onto the atmosphere, maintaining the luminosity through the release of gravitational potential energy (*16*). Assuming that the gas was on a ballistic trajectory, then the time for it to reach its maximum height, and free-fall back, is $2v/g = 640(v/8 \text{ km s}^{-1})$ s. This is very close to the observed interval between the impact and the time of maximum luminosity of 540 s, assuming our previously adopted value of $v = 8$ km s^{-1}. This agreement gives substantial credence to the idea that the luminosity of the impact site is maintained by reentry of the fireball.

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17. The importance of the tunnel of hot gases left by the comet fragment can be seen from the following argument, which shows that without it the breakout time is an order of magnitude longer. If the explosion is treated simply as a point explosion in an exponential atmosphere, then the time for the shock to break out of the atmosphere (t_{bo}) is $\approx \xi(\rho_a h^5/E)^{1/2}$ (*18*), where ρ_a is the atmospheric density at the point of explosion, h is the scale height, E is the explosion energy, and $\xi = 8.9$ is a dimensionless constant (*12*). The point of explosion and the energy released are not independent because they both depend on the size and density size of the impactor. Using the analytic penetration model of MacLow and Zahnle (*14*), we can write $t_{bo} = 500\ (\rho_c/\text{g cm}^{-3})^{2/3}\ (r_c/\text{km})^{1/4}$ s (*12, 14*), where ρ_c is the comet density ($\rho_c = 1$ g cm^{-3} for water ice) and r_c is the comet radius. For typical values of r_c of 0.25 to 2.0 km and of $\rho_c \approx 1$ g cm^{-3}, the breakout time is much longer than the observed interval between the first and second flashes.
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19. We acknowledge the invaluable assistance of the entire Keck Observatory staff and especially thank J. Aycock, A. Conrad, P. Gillingham, W. Harrison, and W. Lupton. These observations were made possible by special observing software written by D. Vezie. K. Zahnle provided many ideas and much inspiration. This work was supported by grants from NASA, NSF, and the Packard Foundation.