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Palomar observations of the R impact of comet Shoemaker-Levy 9: II. Spectra

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Abstract. We present mid-infrared spectroscopic observations from Palomar observatory of the impact of fragment R of comet P/Shoemaker-Levy 9 with Jupiter on 21 July 1994. Low-resolution 8–13 μm spectra taken near the peak of the lightcurve show a broad emission feature that resembles the silicate feature commonly seen in comets and the interstellar medium. We use this feature to estimate the dust content of the impact plume. The overall infrared spectral energy distribution at the time of peak brightness is consistent with emission from an optically-thin layer of small particles at $\sim$ 600 K. Integrating over the spectrum and the lightcurve, we obtain a total radiated energy from the R impact of $\geq 2 \times 10^{25}$ ergs and a plume mass of $\geq 3 \times 10^{13}$ g.

Introduction

In Paper I we described the lightcurves obtained for the R impact at Palomar at 3.2 and 4.5 μm. Here we present 8–13 μm spectra of the evolving impact site, as well as a composite spectral energy distribution at the time of peak flux.[5] The near-infrared lightcurves are also used to estimate color temperatures of the R impact precursor flashes and of the fresh impact site.

Spectroscopic observations

At intervals of 7–10 min during the course of the Palomar R impact observations, low-resolution spectra were taken in three overlapping wavelength intervals to provide complete 8–13 μm coverage with a resolution, $\lambda/\Delta\lambda \approx 100$. All spectra were obtained with a 1″-wide slit oriented parallel to Jupiter's equator and centered on the location of peak brightness measured at 4.5 μm. A total of eight complete 8–13 μm spectra were obtained, beginning at 5:37 UT and ending at 6:45 UT. The first spectrum was taken immediately following the second precursor flash, the second just prior to the peak flux at 5:45 UT, and the remainder at intervals during the decay phase. Separate spectra taken of Callisto at 1:09 UT were used for absolute flux calibration.

Data Analysis

Each 10-second exposure spectral image was reduced by subtracting the off-Jupiter chopped image and removing bad pixels by interpolation; a slight tilt was removed by 'twisting' the images so that the spectral lines were vertical in each spectral image. The wavelength scales were determined from telluric emission lines at known wavelengths in the sky frames for each wavelength segment. Because the airmass of the observations ranged from 2.65 to 5.92, extinction effects are substantial. From measurements of a region of Jupiter well away from the R impact site, we determined a wavelength-dependent extinction coefficient of 0.25–0.9 mag/airmass which was used to correct both the Jupiter and Callisto spectra for extinction effects. Except in the strong telluric ozone band between 9.3 and 9.9 μm, this procedure yielded acceptably consistent spectra.

The fluxes from both the impact site and Callisto were summed over 11 pixels (2.75″) along the slit, resulting in an effective aperture size of 2.75 × 1.0″. Although the slit did not include all the flux from Callisto, we applied no slit throughput corrections since the projected impact spot size perpendicular to the slit of $\sim$ 1.5″ was comparable to Callisto's diameter of 1.2″. The Jupiter to Callisto flux ratios were converted to absolute fluxes using the aperture photometry of *Hansen* [1976], interpolated via a blackbody model. Hansen's Callisto data were adjusted to the circumstances of July 1994 by assuming that brightness temperature scales as $r^{-\frac{1}{2}}$ and flux as Δ^{-2}, where r is the Sun-Jupiter distance and Δ is the Earth-Jupiter distance. Three of the resulting spectra are shown in Figure 1.

Results

The initial spectrum at 5:37 UT and those obtained after 6:00 UT are essentially identical, and show bright-

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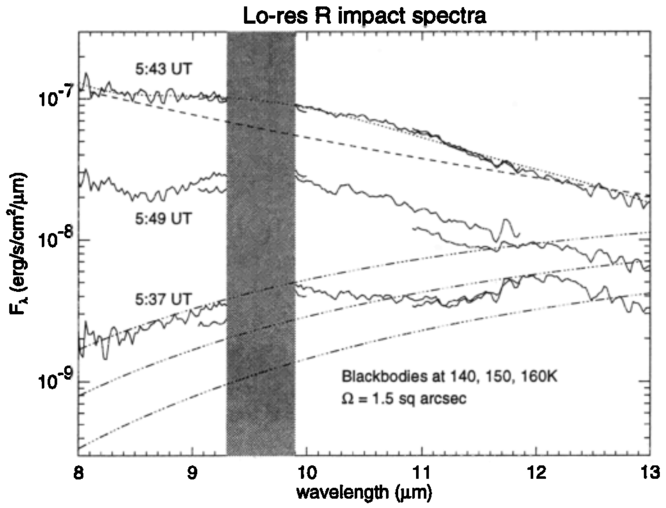

Figure 1. Low-resolution ($\lambda/\Delta\lambda$ = 100) spectra obtained immediately after the second flash (5:37 UT) and before any significant brightening of the R impact site at 10 μm; just prior to the peak brightness of the third flash (5:43 UT); and during the decay phase (5:49 UT). The region of telluric ozone absorption is blanked out by the vertical grey bar. The three segments of the peak spectrum have been separately scaled to the predicted peak fluxes at 5:45 UT, as described in the text. The dotted curve shows the model of silicate dust emission fitted to the peak spectrum (see text), while the dashed curve represents a 2000 K blackbody. Dot-dashed curves show blackbody spectra at characteristic undisturbed jovian temperatures of 140, 150 and 160 K.

ness temperatures consistent with the undisturbed jovian limb. To avoid cluttering the diagram, we have omitted spectra taken after 6:00 UT. We also plot in Fig. 1 blackbody curves for temperatures of 140, 150 and 160 K, spanning the range of undisturbed brightness temperatures expected for Jupiter in this spectral region. The absence of prominent molecular absorption or emission lines in the spectra, especially the usually strong NH_3 lines at 10.3 and 10.7 μm, may be attributable to the very high emission angle ($\geq 75°$). The broad bump at 12 μm is due to stratospheric emission by C_2H_6, while the increase in brightness temperature towards 8 μm is due to stratospheric CH_4 emission.

Near the time of peak brightness at 3.2 and 4.5 μm, a very different 8–13 μm spectrum was observed. The three individual spectral segments, measured in succession, have been scaled in Fig. 1 to their predicted flux levels at 5:45:00 UT, the time of maximum signal at 4.5μm. This allows us to correct for the rapid changes in the absolute flux levels at this time. The scaling factors were derived from a spline fit to the 4.5 μm lightcurve, and range from 1.96 at 8–10 μm to 1.38 at 11–13 μm. Slight mismatches in the spectra in the overlap regions indicate that the uncertainties in this procedure are ~15%. No distinct molecular emission features are seen in the peak spectrum, the smaller ripples being probably due to imperfections in the extinction corrections. Mid-IR spectra taken from the KAO during the R impact [*Sprague et al.*, 1994] also fail to show strong NH_3 emission lines, although those of several other species are prominent.

The spectra taken at 5:49 UT have not been rescaled to a common time, and show small discontinuities due to the fading of the impact site.

Interpretation

Silicate dust emission

The 8 to 13 μm spectral slope at peak brightness is roughly matched by a Rayleigh-Jeans spectrum, suggesting a source temperature of $\geq$ 2000 K (see Fig. 1). Relative to a blackbody, however, the spectrum shows a broad emission feature between 9 and 12 μm. In spectra of T Tauri stars and star-forming regions, a 10 μm bump such as this is usually interpreted as emission from an optically-thin region of small, warm silicate grains. However, the spectrum between 8 and 9 μm is flat or slowly decreasing with wavelength, while the dust emissivity function for astronomical silicates [*Draine and Lee*, 1984] predicts that F_λ should increase with λ, even at a dust temperature, T_d, above the vaporization temperature of silicates. KAO spectra show that methane emission at 7.7 μm is prominent in the first hour after large impacts [*Sprague et al.*, 1994; *Bjoraker et al.*, 1994], and this may account for the upturn below 9 μm in our spectrum.

In the absence of detailed modelling of both atmospheric and dust components, we simply describe the non-dust component of the spectrum (presumably due to CH_4) with a power law and fit the observed F_λ to the following model:

$$F_\lambda = A_d[1-\exp(-\tau_{9.7}Q(\lambda)/Q(9.7))]\,B_\lambda(T_d)+\frac{p_0}{\lambda^n} \quad (1)$$

where $Q(\lambda)$ is the absorption efficiency, assumed to be that of interstellar silicate grains, $\tau_{9.7}$ is the dust optical depth at 9.7 μm, and A_d is the solid angle of dust emission. In the optically-thin limit, $A_d\,\tau_{9.7}$ is the total dust cross-section (in steradians) and is well-determined, although A_d and $\tau_{9.7}$ are not. The best fit to the observed spectrum is obtained for T_d = 370 K, n = 7.5, and $\tau_{9.7} \approx 0.05$, and is shown as the dotted curve in Fig. 1. The model reproduces the form of the 8–13 μm peak spectrum quite well.

Given T_d and the product $A_d\,\tau_{9.7}$, we may obtain the total mass of silicate dust:

$$M_d = \rho_d \frac{A_d \tau_{9.7} \Delta^2}{C_{9.7}} \quad (2)$$

where $\Delta = 8 \times 10^{13}$cm, $C_{9.7} = \frac{3}{4}Q(9.7)/a = 10^4$ cm^{-1} is the absolute volume absorption coefficient at 9.7 μm for "astronomical silicate" grains of radius $a \leq 1$ μm [*Draine and Lee* 1984], and ρ_d = 3.3 g/cm^3 is the as-

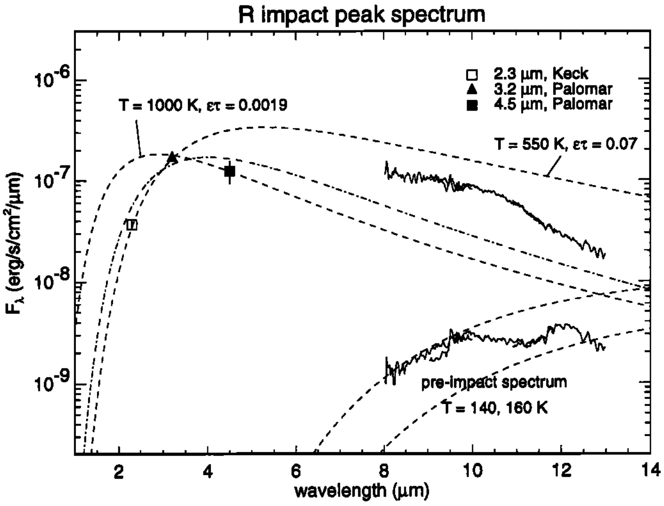

Figure 2. Composite spectrum of the R impact at the time of maximum flux (5:45 UT). Near-IR data are from Fig. 1 of Paper I and from *Graham et al.* [1995] (at 2.3 μm), and the mid-IR spectrum is from Fig. 1. The dot-dashed curve is the 600 K λ^{-1} small-particle haze model fitted to the 2.3, 3.2 and 4.5 μm fluxes, while the dashed curves show blackbody spectra which bracket the near-IR points. The pre-impact 8–13 μm spectrum is included for comparison, along with 140 and 160 K blackbodies. All model spectra assume a 1 square arcsec solid angle.

sumed density of the grains. Our best fit yields a dust mass of 6×10^{12}g. This mass of dust is 20% of the total plume mass estimated below, and about 8% of the mass of a 0.5 km diameter impactor with mean density of 1.0 g/cm^3. (Note that higher dust temperatures would imply correspondingly lower values of $\tau_{9.7}$ and total dust mass; a fit with $T_d = 700$ K yields $M_d = 9 \times 10^{11}$ g. Larger dust particles ($a \geq 1$ μm), on the other hand, could result in a larger total dust mass being 'hidden'.)

If we multiply $A_d\tau_{9.7}$ by 17, the ratio of visible to 9.7 μm interstellar extinction in the solar neighborhood [*Roche and Aitken*, 1984], we get 1.9 square arcsec, equivalent to an optical depth of order unity for the dark impact scars seen in visible images. A silicate composition for these spots might therefore account for both their visible and mid-infrared opacities.

Color temperatures

Ideally, we might hope to determine the evolving temperature of the impact site from the ratio of 3.2 to 4.5 μm fluxes shown in Fig. 1 of Paper I. However, the emission may well be optically thin, and dominated in the near-IR by molecular emission bands. This is especially likely to be the case at 3.2 μm, which is a region of strong methane absorption. Subject to this caveat, we have attempted to calculate color temperatures for the precursor flashes, using the measured peak fluxes at 3.2 and 4.5 μm from Fig. 1 as well as the corresponding fluxes at 2.3 μm measured by *Graham et al.*, [1995]. For the first (bolide entry?) flash, we find a consistent color temperature of 1000 ± 120 K.

The peak of the second flash (the rising plume) gives an unexpectedly low 630 ± 50 K, perhaps because the plume is seen at this time through a significant line-of-sight optical depth of methane. However at 5:36:30 UT, with the plume 20 scale heights higher and thus above sensible atmospheric absorption, we find a color temperature of 950 ± 150 K. This may represent the true plume temperature ~ 90 sec after the impact. Two minutes later we find $T_{\rm col} = 820 \pm 100$ K.

During the growth and decay of the main peak, we find that the color temperature of the R impact site remains relatively constant, varying from a minimum of 600 K at 5:41 UT to a maximum of 1150 K at 5:48 UT. The average color temperature between 5:44 and 6:10 UT is $\sim$1000 K. Although the actual temperatures may differ, the 3.2/4.5 μm flux ratio is strikingly constant over a period in which the absolute fluxes vary by a factor of a hundred. This uniformity of temperature is a strong argument in favor of our interpretation in Paper I that the main flux peak is due to emission from shock-heated re-entering ejecta, rather than from the plume itself, which is predicted to cool rapidly to space [*Zahnle and MacLow*, 1995].

Figure 2 shows a composite spectrum of the R impact at the time of peak flux (5:45 UT), including the 8–13 μm spectrum from Fig. 1, the peak fluxes at 3.2 and 4.5 μm from Fig. 1 of Paper I, and the corresponding peak flux at 2.3 μm measured by *Graham et al.*, [1995]. (Also shown for comparison is the low-resolution spectrum acquired immediately after the precursor flashes at 5:37 UT, scaled to a 1″ square solid angle.) It is impossible to fit all three near-IR points with a single blackbody; the range of plausible temperatures is indicated by the 550 K and 1000 K blackbody spectra fitted to the 2.3/3.2 and 3.2/4.5 μm flux ratios, respectively.

A simple model which at least approximately fits all of the measurements — and is also more physically plausible than pure blackbody emission — consists of a dusty, optically-thin emitting region with a temperature of ~ 600 K and an emissivity which scales as λ^{-1}. The latter is consistent with emission by small solid grains with radii $r \ll \lambda$ and constant refractive index [*van de Hulst*, 1957], and is suggested by the silicate dust fit to the 8–13 μm spectrum in Fig. 1. Such a model is shown as the dot-dashed curve in Fig. 2, fitted approximately to the near-IR points. The deviations of the observed fluxes from the model may be due to CH_4 and silicate emission. The model implies an emissivity-optical depth product of $\epsilon\tau \simeq 0.022$ at 4.5 μm and 0.010 at 10 μm, for an assumed source solid angle of 1 square arcsec. A similar optical depth in stratospheric haze particles at 10 μm is implied by our preliminary analyses of high-resolution spectra of the cooling impact sites in the 8–10 μm region [*Gierasch et al.*, 1994].

Energetics and plume mass

Given a model of the spectrum of the peak emission from the R impact site, and the observed constancy of color temperature during the main peak, we may use the measured 3.2 μm lightcurve in Fig. 1 of Paper I to estimate the total energy radiated by the impact site in the near- to mid-IR region. We adopt the 600 K dust emission model, for which the ratio η of the bolometric flux to F_λ at 3.2 μm is 6.03 μm.[6] Making the further assumption of an isotropic radiator, the total radiated energy is then given by

$$E = \frac{4\pi\Delta^2\eta c}{\lambda^2} \int F_\nu dt. \tag{3}$$

We find a total radiated energy of $\geq 2.2 \times 10^{25}$ ergs, or 2% of the total kinetic energy of a 0.5-km diameter icy comet impacting Jupiter at 60 km/s. This estimate is probably a lower limit because of (i) the emission which occurs during the first $\sim$ 40 sec when the fireball is behind the limb, and (ii) possible preferential emission in a direction away from the Earth. Probably the biggest unknown in this calculation is the uncertain geometry of the impact site. *Zahnle and MacLow* [1995] have taken the first steps towards a more realistic model of the observed lightcurve.

Note that essentially all of this energy is received from the shock-heated re-entry phase; the flashes due to the bolide and plume, as interpreted in Paper I, contribute a negligible fraction of the total radiated energy. Equating the radiated energy to the kinetic energy of the descending plume, for an assumed vertical re-entry velocity of 12.5 km/s, we obtain a lower limit to the total plume mass of 3×10^{13} g.

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[6]For a λ^{-1} emissivity, η reaches a minimum of 3.75 at 900 K, and then increases to 6.1 at 1500 K.

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