Thermal Infrared Imaging Spectroscopy of Shoemaker–Levy 9 Impact Sites: Temperature and HCN Retrievals

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We present high-resolution 8–14 μm observations of Shoemaker–Levy 9 sites conducted on July 20, 30, and 31 1994 UT at the NASA Infrared Telescope Facility. Stratospheric heating was detected from strong enhancements of methane emission near 8.1 μm over areas at least 15,000 km wide around the K site observed 23 hr after impact and around the L site 11 hr after impact. The intensity distribution between strong and weaker CH₄ lines implies that the stratospheric heating was primarily confined to pressures less than 500 μbar. The L site temperature increased by 80 ± 10 K at 5 μbar, but did not exceed 20 K around 1 mbar or 10 K around 10 mbar. The older K site was still 30 ± 5 K warmer than the surroundings at the 10-μbar level. The excess thermal energy stored in the upper jovian stratosphere was $3.1 \times 10^{36}$ erg over the L site, and $2.7 \times 10^{36}$ erg over the K site at the time of the observations. Comparison with numerical simulations indicates that a large fraction (~20%) of the kinetic energy of the L plume was transferred to the jovian atmosphere and not immediately radiated away. Acetylene line emission near 13.4 μm was enhanced over an area ~18,000 km wide centered on the E site 2.6 days after impact. Radiative transfer models of this emission indicate temperatures 37 ± 7 K higher than nominal around 3 μbar. No such enhancement was seen in CH₄ spectral images, implying that the temperature perturbation did not significantly extend below the ~20-μbar level. The H site observed simultaneously was 12 ± 5 K warmer than the surroundings 1.4 day after impact. C₂H₂ lines were still slightly more intense over the K + W and Q1 sites on July 30 and 31, 8 to 10 days after impact. These observations can be interpreted either by temperature differences of about 13 and 10 K respectively in the 3-μbar region, or by an increase in the C₂H₂ column density of $2.5–5 \times 10^{17}$ molecule cm⁻². Emission from hydrogen cyanide lines around 13.4 μm was detected over all sites observed. The mass of HCN produced by all fragments is estimated to be $1.1 \pm 0.4 \times 10^{13}$ g. A consistent interpretation of the different pieces of information available suggests that the H plume was richer in dust than the E or A plume.

1 INTRODUCTION

The collision of Comet Shoemaker–Levy 9 (SL9) with Jupiter caused major atmospheric disturbances over large areas centered on the impact sites. Besides the most visible
presence of long-lived impact debris particles, many new atmospheric species were injected in the high stratosphere (e.g., Lellouch et al. 1995, Noll et al. 1995) and persisted from weeks to months. Stratmospheric temperatures locally underwent dramatic elevations, still detectable a few days after the impacts (Orton et al. 1995).

We report here on high-resolution 10-μm observations of the SL9 impact sites conducted in July 1994 with the Irshell instrument at the NASA Infrared Telescope Facility (IRTF) atop Mauna Kea. Irshell, an array spectrometer developed at the University of Texas (Lacy et al. 1989), was one of the four Cassegrain focus instruments selected by the IRTF Science team 3 for the observing campaign. High-resolution spectroscopy in the 8–13 μm atmospheric window clearly appeared as a powerful means of investigating the expected thermal and chemical changes induced by the SL9 impacts. This broad window contains rovibrational bands from various molecules of atmospheric interest and was thus considered as a primary target. Its location in the thermal infrared allied with the high sensitivity of the Irshell spectrometer allows the detection of thermal emission from the cold jovian stratosphere (110–180 K). In addition, the high spectral resolution available with Irshell permits the observation of individual molecular lines. The various gaseous and particulate contributions to the thermal emission can then be disentangled and molecular signatures unambiguously identified. Our goals were (i) to measure stratmospheric temperatures by imaging spectral emission lines from known constituents (CH4 and C2H2); and (ii) to search for molecular lines from various molecules which could have been produced or injected in Jupiter’s high atmosphere where they are normally absent (mainly NH3, H2S, and HCN).

The Irshell observations on July 20, 25, 30, and 31 1994 UT led to the detection of NH3, HCN, and C2H4 in the stratosphere of the planet over various impact sites. An additional continuum emission, presumably from silicate grains, was furthermore present in these regions. CH4 and C2H2 line observations on July 20 showed large perturbations in the stratospheric temperatures of the fresh impact sites. In this paper, we present the available set of CH4 and C2H2 spectral observations and derive quantitative information on the temperature perturbations induced by the impacts. We also report the detection of HCN emission over all sites observed and present resolved maps of this emission. These data are analyzed to infer column densities and total masses of HCN produced by the impact processes. Observations of NH3, C2H4, and the silicate dust emission features are presented in a companion paper (Griffith et al. 1996).

2. DATA ACQUISITION AND REDUCTION

The Irshell spectrometer was mounted at the Cassegrain focus of the IRTF on the nights of 1994 July 20, 25, 30, and 31 UT. A new 20 spatial × 64 spectral element Si:As IBC array, provided by Hughes Aircraft, was used during this run. The 17-arcsec long slit was oriented along the east–west planetocentric direction allowing for simultaneous observations of 20 different positions separated by 0.83 arcsec (except for a gap in the center between Rows 10 and 11). Spectral maps of the impact regions were obtained by scanning the telescope in Jupiter’s north–south direction with steps of 1 arcsec. The slit width was set to 1.8 pixel, yielding a resolving power of ~15,000 and a spatial resolution of 1.5 arcsec, corresponding to 5600 km at Jupiter’s distance.

The observations presented and analyzed in this paper are summarized in Table I. For the CH4 observations, the grating was set to cover the interval 1233- to 1235.5-cm–1 or 1232.5- to 1235-cm–1 that includes a relatively strong methane line at 1233.455 cm–1 and weaker lines at 1233.006, 1233.147, 1234.226, 1234.979, and 1235.061 cm–1 (Fig. 1). The intrinsic intensity of the weaker lines is typically a hundred times weaker than that of the strong line around 180 K, allowing us to probe simultaneously different pressure levels in the stratosphere as discussed later. The interval 743–745 cm–1 observed on July 20 and 30 includes the R(5) C2H2 line at 743.265 cm–1 and the R(10) HCN line at 744.458 cm–1 (Fig. 2). The interval 746.5–748.5 cm–1 observed on July 31 includes both the R(7) C2H2 line at 747.963 cm–1 and the R(11) HCN line at 747.405 cm–1 (Fig. 2).

The “nod” observing mode (Lacy et al. 1989) was used, the telescope being nodded with an amplitude of 40 arcsec and a period of a few seconds. We applied the procedures for flat fielding, correction of atmospheric absorption, and intensity calibration described in Lacy et al. (1989) and Bézard et al. (1995). The uncertainty on the absolute intensity calibration is ~10% in regions of high telluric transmission. Unfortunately, the new array used in July 1994 happened to exhibit many “bad” pixels (dead or hot) for which the signal was afterward interpolated between the pixels spectrally adjacent. The whole 14th row was not useable and was interpolated between adjacent rows. In addition, the gap between the 10th and 11th rows was filled in by interpolation, creating 21 rows of data in the images presented hereafter.

3. OBSERVATIONS

Typical spectra of the CH4, C2H2, and HCN lines recorded during our run are shown in Figs. 1 and 2. Jovian lines in these spectra are Doppler-shifted by −0.095 cm–1 (CH4) and −0.065 cm–1 (C2H2 and HCN) because of the...
Jupiter–Earth motion and the rotation of the planet. We generated images of these molecular emission lines and of the nearby continuum. Continuum and line intensities were derived for the spectrum of each spatial pixel by fitting the relevant spectral region with an analytical function consisting of a Gaussian line superimposed on a quadratic background. The set of free parameters was derived through an algorithm minimizing the value $\chi^2$ of the fit between model and observations. Bad or noisy array pixels were not considered in the fitting procedure. Continuum and line maps are shown in Figs. 3–10. Rows are labeled in 0.83 arcsec pixels, and columns in 1.0° scan steps.

In addition to these maps, a sketch of Jupiter’s mapped region is displayed with the center of the visible impacts placed on a grid having a step of 10° in latitude and 30° in longitude and coordinates in arcsec from the disk center. The locations of the impacts were taken from Hammel et al. (1995). The absolute pointing accuracy of these observations is intrinsically no better than 2 arcsec. However, reconstructing the limb from the continuum maps whenever possible allowed us to improve the accuracy to about 1 arcsec.

Figure 3 shows images of the CH$_4$ emissions centered on July 20, 08:57 UT (Scan 20–32). The prominent bright feature present at the west limb of the planet (Col. 3, Rows 2–3) is the L site. This image was recorded 11 hr after impact. Also noticeable in the same image is the K site (centered on Row 17) observed 23 hr after impact. This strong CH$_4$ line at a rest frequency of 1233.455 cm$^{-1}$ is 3.5 times more intense than nominal over the L site, and 1.6 times more intense over the K site. The maximum intensity is observed for the last column of the scan; considering the pointing uncertainties, it is possible that the maximum perturbation takes place further south and was not recorded during this scan. The longitudinal extent of the bright feature observed over the K site in Col. 3 is 4.5 ± 0.5 arcsec at half intensity, for a 1.5-arcsec resolution. This corresponds to an emitting size of 16,000 ± 2,000 km, similar to that observed in dust images of the same site (Griffith et al. 1996) and to 10-µm images of the L site, 2 hr after collision (Lagage et al. 1995). This similarity argues that Col. 3 is probably close enough to the impact latitude so that the observed temperature perturbations are not far from the maximum ones present on the sites. The L site is seen close to the west limb at a jovian airmass of 5.3. As a consequence, the longitudinal extension of the perturbed region as observed by the instrument is less than the 1.5-arcsec spatial resolution. Assuming an emitting area of 16,000 ± 2,000 km, we calculate that for the pixel showing maximum intensity (Col. 3, Row 3), the L hot spot fills 50 ± 10% of a resolution element. It is noteworthy that no similar enhancements are seen in the “CH$_4$ weak” image; this has strong implications on the altitude of the atmospheric levels perturbed by the impacts as discussed in Section 5.

In addition, the impact sites are not visible in the continuum map which only shows the expected limb-darkening behavior. The nondetection of enhanced continuum emission around 8 µm contrasts with our observations at 10.5 and 11.0 µm which show a strong continuum emission over the K site on the same date (Griffith et al. 1996). As discussed by Griffith et al., this behavior is consistent with silicate dust being responsible for the 10.5-µm emission. Figure 4 shows images of the continuum and “CH$_4$ strong” line intensity on July 20, 04:58 UT at latitudes where the A and E sites are visible (Scan 20-15). Site A was observed 3.3 days after impact, and Site E 2.6 days after impact. The CH$_4$ line shows no enhancement exceeding 10% over either site when compared to unperturbed regions at the same latitude. Similar maps were obtained on July 31, 03:41 UT (Scan 31-12) (Fig. 5). The K + W site, observed 11.7 days after impact K (8.8 days after W), no longer shows any detectable enhancement of

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<table>
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<th>Date (UT)</th>
<th>Scan number$^a$</th>
<th>Molecule</th>
<th>Spectral range (cm$^{-1}$)</th>
<th>Resolution (cm$^{-1}$)</th>
<th>Integration time$^b$ (sec)</th>
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<td>1232.5–1235</td>
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<td>68</td>
<td>K, L</td>
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<td>14, 15</td>
<td>CH$_4$</td>
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<td>68</td>
<td>A, E</td>
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<tr>
<td>05:59–06:28</td>
<td>19, 20</td>
<td>C$_2$H$_2$, HCN</td>
<td>743–745</td>
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<td>34</td>
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<td>B, D, G, H, N, Q1, Q2, R, S</td>
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$^a$ In the text and the figures, scans are identified by the date (20, 30, or 31) followed by the scan number (for example, 20-31).

$^b$ ON source integration time per position on the disk.
**FIG. 1.** Irshell spectra of Jupiter including a strong CH$_4$ line at a rest frequency of 1233.455 cm$^{-1}$ and several weaker CH$_4$ lines at a resolution of 0.07 cm$^{-1}$ (lines with squares). These spectra extracted from Scans 20-15 and 20-32 were recorded outside of the impact sites but at the same latitude. The telluric transmission for each observation is shown on the upper panel. The terrestrial atmospheric absorption line is at the rest frequency. The jovian lines are Doppler-shifted due to the Jupiter–Earth motion (~0.11 cm$^{-1}$) and the rotation of the planet. 1-$\sigma$ random noise error bars are indicated at the peak of the 1233.455-cm$^{-1}$ line and away from this line. The thicker solid lines are synthetic spectra calculated with the nominal temperature and CH$_4$ vertical profiles shown in Fig. 11.

the CH$_4$ line. An upper limit of 10% can be set on any possible remaining enhancement.

Images of the C$_2$H$_2$ and HCN emission intensities are displayed in Figs. 6–10. On July 20, 06:04 UT (Scan 20-19), the E site, observed 2.6 days after impact, was visible as well as, near the East limb, the H site observed 1.4 day after impact (Fig. 6). The brightest spot in the C$_2$H$_2$ image is at the location of the E site (Rows 8 and 9). Here, the acetylene line is 70% more intense than in regions outside the impacts observed at similar airmasses (Col. 1, Row 17). The H site is also distinguishable at the East limb, although with less contrast. Finally, the A fragment impacted Jupiter 3.4 days before these observations, only ~1.5 pixel west of Row 1. This row appears slightly brighter than Rows 2 and 3, suggesting that we may be seeing temperature perturbations at the eastern edge of the A site. The observed intensity enhancement very likely results from warmer stratospheric temperatures over the impact sites (see Section 6). As discussed above, no enhancement in excess of 10% was seen in the methane lines over the A and E sites, which constrains the maximum depth of the temperature perturbations. HCN emission is prominent on the E site, and covers a 18,000–km broad area (at half maximum). It is also detected on the H site, and on the eastern edge of the A site at the lower end of the infrared array. The analysis of the HCN observations in
FIG. 2. Infrared spectra of the K and Q1 impact sites on Jupiter in the ranges 743–745 and 746.5–748.5 cm\(^{-1}\), extracted from Scans 30-14 and 31-22 respectively (lines with squares). The spectral regions include C\(_2\)H\(_2\) lines at rest frequencies of 743.265 and 747.963 cm\(^{-1}\) and HCN lines at 744.458 and 747.405 cm\(^{-1}\). Other weaker emission features are due to weak C\(_2\)H\(_2\) lines. The spectral resolution is 0.07 and 0.06 cm\(^{-1}\) respectively. Data corresponding to regions where the telluric transmission, shown in the upper panel, is less than 20% are not plotted. The jovian lines are Doppler-shifted due to the Jupiter–Earth motion (−0.07 cm\(^{-1}\)) and the rotation of the planet. 1-\(\sigma\) random noise error bars are indicated at the peaks of the C\(_2\)H\(_2\) and HCN lines. The thicker solid lines are synthetic spectra calculated with the nominal C\(_2\)H\(_2\) vertical profile shown in Fig. 11 and a temperature profile slightly warmer than nominal above the 15-\(\mu\)bar level; the HCN mole fraction in the upper stratosphere was adjusted to best reproduce the observed lines (see text).

terms of column density and mass are presented in Section 7.

Figures 7 and 8 show images of emission intensities for C\(_2\)H\(_2\) and HCN observed on July 30. HCN emission is clearly visible over the K + W site (Rows 8–21) and at the eastern edge of the L site (Rows 1–5) (Scan 30-14, Fig. 7). It is maximum near latitude −41 ± 4° and longitude 285 ± 5° (System III) and corresponds to the K impact location within uncertainties. The HCN emission extends over longitudes 250 to 305°. The HCN map in Fig. 8 (Scan 30-15) exhibits an extended bright region extending from the western limb to a longitude of 325 ± 5°. This region corresponds to the L and G impact sites which can no longer be distinguished. We also note that the C\(_2\)H\(_2\) map in Fig. 7 shows a spot ~20% brighter than its surroundings. This spot is centered near (Cols. 3–4, Rows 10–11) ~1.5 arcsec west of the peak of the HCN emission due to the K and W impacts. It may reveal the remnant of the stratospheric heating from the W impact which occurred 8 days before the observations, or a true C\(_2\)H\(_2\) concentration enrichment over the site. No enhancement exceeding 10% is observed in the C\(_2\)H\(_2\) line intensity over the G + L complex (Fig. 8), possibly because the impacts are older as discussed in Section 8a.

Finally, Figs. 9 and 10 show maps of the C\(_2\)H\(_2\) and HCN emissions observed on July 31 between longitudes 20° and 110° (Scans 31-21 and 31-22). HCN is detected over the whole longitude range observed between latitudes −35° and −55°. The emission is maximum near longitude 65°, which corresponds to the location of the Q1 impact. The largest clump extends between longitudes 35° and 90° and includes the R, Q2, Q1, B, and N sites. The eastern edge of the H site is visible at longitudes larger than 90° (Rows 1–3 in Fig. 10). The HCN emission observed at longitudes
lower than 35º (Rows 19–21 in Fig. 10) most likely originates from the G impact. The weak D and S sites which fall between the G site and the R–Q2–Q1–B–N complex cannot be distinguished. The C2H2 map in Fig. 9 shows a brighter region (Cols. 5–7, Rows 7–15) that corresponds approximately to the R–Q2–Q1–B–N complex seen in the HCN map. This bright spot is also visible in Fig. 10. The increase in the C2H2 intensity amounts to ~15%. In Fig. 10, the brightest feature in the last column of the C2H2 map is enhanced emission from the Southern auroral zone.

4. RADIATIVE TRANSFER MODEL

We have compared our observations to synthetic spectra generated from a line-by-line radiative transfer program to derive the HCN abundance over the observed impact sites, and to constrain stratospheric temperatures using CH4 and C2H2 observations. H2–H2 and H2–He collision–induced opacity was modeled through the formulation of Birnbaum and Cohen (1976) and Cohen et al. (1982), using laboratory measurements by Dore et al. (1983) and Bachet (1988). A helium mole fraction of 0.10 was used in the calculations. We included molecular absorption from CH4, CH3D, C2H2, and HCN. Line parameters (positions, intensities, energy levels) were extracted from the GEISA 1991 line compilation (Husson et al. 1991). A Voigt profile was used for the molecular lineshape up to 10 cm−1 from line center. The Lorentz halfwidths of the CH4 (and CH3D) lines were taken as 0.075 cm−1 atm−1 at room temperature with a temperature dependence as T−0.55 (Varanasi and Tejwani 1972). Helium and hydrogen broadening coefficients for C2H2 were taken from Varanasi (1992). For the two observed HCN lines (R(10) and R(11)), we used a value of 0.13 cm−1 atm−1 for room temperature, based on measurements of N2–broadened lines in the ν2 band of HCN.
Schmidt et al. (1992) and on the similarity of the $\text{H}_2\text{O}$ and $\text{N}_2$-broadening coefficients for the $J = 4$ line (Rohart et al. 1987). The Lorentz linewidths were assumed to vary as $T^{-0.75}$. We did not include any opacity due to clouds besides the molecular one.

Thermal emission was calculated under the assumption of LTE for all molecules. This assumption is expected to break down around the 0.5-μbar level for the $v_4$ band of methane (Appleby 1990, Drossart et al. 1993). It should thus remain valid for our calculations since all of the emission in the $\text{CH}_4$ lines observed here originates from below the 2-μbar level (Fig. 12). The LTE approximation should also be valid for the $v_5$ band of acetylene. The collisional deactivation rate for this band is 7 times larger at room temperature than for the $v_4$ band of methane (Häger et al. 1981), which more than compensates for the twice larger Einstein coefficient.

Calculated spectra were convolved with a Gaussian profile having a full width at half maximum equal to the resolution of the observations (Table I).

The temperature profile included in our model is a composite. It consists of the “STZ Cold” profile from Griffith et al. (1992) (displayed in their Fig. 4) for pressures larger than 30 mbar. As shown in Figs. 1 and 2, continuum radiances calculated with this profile agree with the observed values within the calibration uncertainty. At lower pressures, the temperature profile was adjusted until it yields a good reproduction of the methane spectra observed outside the impacts (Fig. 1). The temperature profile we obtained is displayed in Fig. 11. In calculating the methane spectra, we used the mixing ratio profile proposed by Gladstone et al. (1996) and shown in Fig. 11. This profile was derived assuming a deep $\text{CH}_4$ mixing ratio equal to $2.2 \times 10^{-3}$ (Gautier et al. 1982) and an eddy mixing coefficient at the homopause of $1.4 \times 10^6 \text{ cm}^2 \text{ sec}^{-1}$ (Atreya et al. 1981).

Shown in Fig. 12 are the corresponding contribution functions at the peak of two $\text{CH}_4$ lines, defined as

$$
\int_{n_n}^{n_f} B_r(T) \frac{d \epsilon}{d \ln p} f(\nu - n_0) d
\nu dI_0,
$$

where $B_r(T)$ is the Planck function at temperature $T$, $\tau$ is the slant path optical depth at pressure level $p$, $f$ is the convolution function defined over the interval $[-\Delta \nu, +\Delta \nu]$ for the transitions $n_0 \rightarrow n_f$.
\[ \Delta \nu \] and \( I_{0} \) is the convolved radiance at wavenumber \( \nu_{0} \). An airmass of 1.50 was used in these calculations. Emission from the strong CH$_4$ line at 1233.455 cm$^{-1}$ originates mostly from the region 1.5 to 20 mbar with a maximum contribution around 6 mbar. A small fraction of the emission however originates from a region centered at 30 \( \mu \)bar (10–100 \( \mu \)bar at half maximum). The contribution function for the weaker line at 1233.147 cm$^{-1}$ peaks around 12 mbar (0.5–30 mbar at half maximum) and is essentially confined to pressures larger than 0.1 mbar in contrast to the stronger CH$_4$ line.

Synthetic spectra significantly underestimate the observed continua in the wings of the CH$_4$ lines, especially in the region 1234.4–1234.8 cm$^{-1}$ (Figs. 1 and 13). The discrepancy may arise from improper modeling of the tropospheric opacity, such as an overestimation of the far wing opacity of methane lines. It does not however affect the present analysis as we are only interested in the line emission intensities.

To model the C$_2$H$_2$ observations, we first used the baseline photochemical profile proposed by Gladstone et al. (1996) and shown in their Fig. 3. We compared synthetic spectra based on this C$_2$H$_2$ profile and on our nominal temperature profile with observations recorded outside of the impact sites. For the July 20 observations (Scan 20-19 in Fig. 6), our “reference” spectrum is that of (Col. 1, Row 17) recorded at an airmass similar to that of Site E but at lower latitudes as mentioned in Section 3. For the July 30 and 31 data, we used spectra at the latitude of the impacts and outside of the brighter spots described in Section 3. Calculated spectra yield C$_2$H$_2$ line intensities which are much too large compared to these reference spectra. We then chose to deplete Gladstone et al.’s profile by a constant factor, and found that a factor of 3.6 was needed to reproduce the reference lines. The corresponding C$_2$H$_2$ profile is displayed in Fig. 11.

The contribution function at the peak of the acetylene line (743.265 cm$^{-1}$) is shown in Fig. 12. About 40% of the stratospheric emission is confined above the 0.1-mbar level, with a maximum contribution near the 3-\( \mu \)bar level (2–6 \( \mu \)bar at half maximum). A broader contribution originates from the pressure range 0.3 to 40 mbar. This behavior results from the shape of the C$_2$H$_2$ mixing ratio profile, strongly increasing with height in the stratosphere, with a maximum near 7 \( \mu \)bar. The tropospheric peak in the contribution function near 400 mbar reflects the opacity from the H$_2$–He continuum.

**FIG. 5.** Same as described in the legend to Fig. 4 for Scan 31-12. LCM is 298° W.
5. ANALYSIS OF CH\textsubscript{4} OBSERVATIONS

(a) July 20 1994 UT: Sites K and L

Figure 13 shows a comparison between CH\textsubscript{4} spectra observed over the L and K sites and outside the impacts on July 20, 08:57 UT. As discussed in Section 3, the strong methane line at 1233.455 cm\textsuperscript{-1} is strongly enhanced over the K and L sites. This enhancement most likely results from a temperature increase in the upper stratosphere rather than a modification of the CH\textsubscript{4} abundance profile. The first argument in favor of a temperature increase is that it was not observed over sites older than 4 days either with Irshell (Figs. 4–6) or in MIRAC2 7.85-\textmu m images (Orton et al. 1995). The 2-day time scale observed (Orton et al. 1995) is much shorter than the lifetime of methane or the vertical mixing time at the altitudes affected by the plume fallback \( p < 0.1 \) mbar (Gladstone et al. 1996). The second argument deals with mass considerations. The mass of the atmosphere above \( p = 0.1 \) mbar over an area 15–20,000 km broad is on the order of \( 10^17 \) g, 1% of which is methane. This is \( \sim 1000 \) times larger than the predicted mass of a fireball created by a \( 10^{14} \) g fragment. Methane could be present in the plume after the reentry shock if the O/C ratio is less than 1 (Zahnle 1996), but only at the \( 10^{13} \) g level. Therefore, the mixing of the plume with jovian air at pressures less than 0.1 mbar should not significantly alter the methane mixing ratio in this region. Also, the atmospheric mass above \( p = 0.1 \) mbar is \( \sim 100 \) times larger than the mass of dry jovian air shocked at \( T > 2000 \) K during the plume reentry, a temperature above which methane may be processed into more complex hydrocarbons (Zahnle 1996). Therefore, composition changes induced by shock chemistry should not have altered significantly the methane abundance profile in the stratosphere. Third, we note that the total mass of cooler jovian air lifted from the troposphere is probably in excess of \( 10^{16} \) g (Griffith et al. 1996), resulting in a local contamination of the stratosphere with tropospheric air. However, this “pollution” is ineffective even at pressure levels less than \( \sim 10 \) \textmu bar, where the nominal CH\textsubscript{4} mixing ratio becomes significantly lower than the tropospheric value. Test calculations with a constant mixing ratio in the whole atmo-
sphere instead of Gladstone et al.'s (1996) photochemical profile yield a modest 5% increase in the line emission. Consequently, we assume hereafter that the increase in CH$_4$ emission is entirely due to perturbations in the thermal structure, and we use our nominal CH$_4$ mixing ratio profile in all synthetic calculations.

The major characteristic of the CH$_4$ emission enhancement is that it affects almost exclusively the strong line and not the weaker lines. This can be understood only if the temperature increase is confined to the high stratosphere, in a region where the contribution function of the weak lines is negligible, roughly above the 0.1-mbar region (Fig. 12). Such a perturbation can still affect the emission in the strong CH$_4$ line because its contribution function exhibits a significant secondary peak in the region 0.01 to 0.1 mbar. On the other hand, all CH$_4$ lines are largely insensitive to any temperature perturbation above the ~0.01-mbar region because of the rapid falloff of the methane mixing ratio above this level. Our models of the CH$_4$ spectra for the L and K sites are presented below.

As discussed in Section 3, we assumed that the L site fills in 50 ± 10% of the field of view at a jovian airmass of 5.3. The rest of the field of view divides into the jovian "nominal" background seen at an airmass of 3.3 (25 ± 10%) and an area off the planet with a null flux (25%). The K site was observed at an airmass of 1.4, near the central meridian.

In a first class of models, we perturbed the nominal temperature profile by a fixed amount ($\Delta T_0$) above a cutoff level ($p_0$) which could represent the mean pressure of the reentry shock. This is the type of model employed by Lellouch et al. (1995) and Marten et al. (1995) in their analysis of millimeter lines of CO, CS, and HCN detected over the impact sites. In Fig. 14, the spectrum of the L site is compared with synthetic spectra for $p_0 = 1, 0.1, \text{ and } 0.01$ mbar. In all cases, $\Delta T_0$ was adjusted to reproduce the intensity of the strong CH$_4$ line at 1233.455 cm$^{-1}$. Clearly, profiles with $p_0 = 1$ or 0.1 mbar produce too much intensity in the weak CH$_4$ lines. Dashed lines in Fig. 15 indicate the maximum temperature increase allowed by the weak CH$_4$ lines ($1233.147$ and $1234.375$ cm$^{-1}$) as a function of pressure level $p_0$. The criterion for acceptability is that $\Delta T_0$ should not yield intensities for these weak lines exceeding those observed by more than 50%. Only limited temperature changes can be tolerated in the lower stratosphere for both sites: less than ~20 K for $p_0 \geq 1$ mbar, less than ~10 K
FIG. 8. Same as described in the legend to Fig. 6 for Scan 30-15. LCM is 306° W.

for \( p_0 \gtrsim 10 \) mbar. For the L site, only profiles with \( p_0 \) less than 40 \( \mu \)bar can reproduce the intensity of the strong CH\(_4\) line while not significantly enhancing the intensity of the weak lines. On the other hand, values of \( p_0 \) that are too low lead to unacceptably high temperatures. An analysis of CO emission lines observed at 4.7 \( \mu \)m over the L site 4.5 hr after impact (Maillard et al. 1995) provides an additional constraint. These observations indicate a temperature of 274 ± 10 K where the CO column density is \( \sim 10^{16} \) molecule cm\(^{-2}\), probably around 2 \( \mu \)bar. We regarded this temperature as an upper limit to the thermal profile of the L site 11 hr after impact. This condition is fulfilled when \( p_0 \) is larger than 8 \( \mu \)bar (Fig. 15). The spectrum of the K site provides less stringent constraints than for the L site because it was observed at lower airmass and later when it was cooler. Following the same criteria, we find that \( p_0 \) must lie between 800 and 5 \( \mu \)bar for this class of models.

In a second step, we considered thermal profiles with no discontinuity and in which the temperature perturbation increases with height above a certain level \( p_1 \). We assumed that \( T \) then varies as the inverse of the pressure raised to some power \( n \). This type of profile is supported both by observational constraints (Maillard et al. 1995) and models (Zahnle 1996) which suggest that temperature increases upward within the plume after the reentry shock (see Section 8). For this smoother type of profiles, the pressure level \( p_1 \) can be deeper than \( p_0 \) as defined in the previous models because the perturbation is still zero at \( p_1 \) and increases with height above it. For a given pressure level \( p_1 \), the power \( n \) was adjusted to reproduce the intensity of the strong CH\(_4\) line (1233.455 cm\(^{-1}\)). We found that fitting simultaneously the weak and strong lines in the spectrum of the L site requires \( p_1 \) to be less than 500 \( \mu \)bar. A lower limit on \( p_1 \) is more difficult to estimate. If the temperature at 2 \( \mu \)bar is constrained to be less than 274 ± 10 K, \( p_1 \) must be larger than 100 \( \mu \)bar. However, the pressure level where the CO temperature was actually 274 ± 10 K 4.5 hr after impact L (Maillard et al. 1995) is poorly defined and depends on the CO vertical distribution in the plume. The uncertainty on this pressure level could be as high as an order of magnitude on each side. We thus regard 100–500 \( \mu \)bar as the most likely range for \( p_1 \) but cannot exclude values as low as 5 \( \mu \)bar. The K site spectrum does not provide strong constraints since a solution temperature profile can be found for any value of \( p_1 \) smaller than 10 mbar: the lapse rate is then sufficient to ensure that the
weak lines are almost not enhanced while the strong line is fitted. Figure 16 presents the solution profiles for $p_1 = 20, 100, \text{ and } 500 \mu\text{bar}$, the maximum allowed pressure. All profiles with $20 < p_1 < 500 \mu\text{bar}$ meet around the 5-\mu{bar} level for the L site and the 10-\mu{bar} level for the K site, with temperature respectively reaching 250 and 200 K (compared to a "quiescent" value of 170 K). These pressure levels appear to be those for which the temperature perturbation is best determined from our data. Taking into account calibration uncertainties and, in the case of L, an additional uncertainty from the filling factor, we conclude that the temperature perturbations amount to $80 \pm 10$ K near 5 \mu{bar} for the L site, and $30 \pm 5$ K near 10 \mu{bar} for the K site. The temperature steps, $T_0$, in our first class of models are similar to these values if they occur at about a scale height deeper.

(b) July 20 1994 UT: Sites A and E

As discussed in Section 3, the A and E sites observed in Scan 20-15 do not exhibit any intensity enhancement in the CH$_4$ lines larger than 10\% (Fig. 4). Calculations performed with temperature models for various values of $p_1$ (20–500 \mu{bar}) indicate that this upper limit imposes a maximum temperature increase of 10 K around the 10-\mu{bar} level.

(c) July 31 1994 UT: Sites K and W

On July 31, the K + W site observed in Scan 31-12 no longer exhibits a larger intensity of the 1233.455-cm$^{-1}$ CH$_4$ line (Fig. 5). As above, the maximum temperature enhancement consistent with these observations is on the order of 10 K near 10 \mu{bar}.

6. ANALYSIS OF C$_2$H$_2$ OBSERVATIONS

(a) July 20 1994 UT: Sites E and H

C$_2$H$_2$ emission is strongly enhanced (~70\%) over the E site observed 2.6 days after impact, and less markedly over the H site observed 1.4 day after impact (Fig. 17). Most of this enhancement very likely results from an increase in the temperature rather than in the mixing ratio. A mixing ratio as high as $3 \times 10^{-4}$ above the 0.1-mbar level would be required to reproduce the enhancement using our nominal
temperature profile ($1 \times 10^{-2}$ if restricted to $p < 0.01$ mbar). The corresponding column density would then be on the order of $3 \times 10^{18}$ molecule cm$^{-2}$. This is about 30 times larger than the upper limit derived from HST UV observations of the G site (Atreya et al. 1995). We note however that comparison of our observations with the HST UV results might be inappropriate since the HST/FOS had an aperture diameter half of ours and only observed the core of the impact site. If acetylene production predominantly occurred in the outskirts of the perturbed sites, several thousands of kilometers away from the entry location (as in Zahnle’s (1996) chemical–dynamical model), our observations may have detected more C$_2$H$_2$ than HST/FOS spectra did.

Chemistry at work in dry jovian air shocked at $T > 3000$ K is expected to produce acetylene with a maximum mass mixing ratio of 0.01 (Zahnle 1996). According to Zahnle’s model, $6 \times 10^{14}$ g of jovian air are shocked at these temperatures for the biggest impactors. Assuming a plume extension of $\sim 18,000$ km (as visible on our images), the C$_2$H$_2$ column density thus produced would be at most $5 \times 10^{16}$ molecule cm$^{-2}$, and probably much less for the smaller E fragment. This quantity is similar to the upper limit derived by Atreya et al. (1995) and again much lower than what would be needed to reproduce the C$_2$H$_2$ observations. Finally, we note that no intensity increase as large as that detected for Site E on July 20 was observed for larger times than the upper limit derived from HST UV observations of the G site (Atreya et al. 1995). We note impact sites on July 30 and 31. This would not be expected if the enhancement resulted from an increase in the C$_2$H$_2$ abundance, since the lifetime of this compound is on the order of a year in the region $10$ to $100$ $\mu$bar (Gladstone et al. 1996). We will therefore hereafter assume that the stronger C$_2$H$_2$ line intensities result from a warmer temperature profile.

In contrast to the C$_2$H$_2$ line, only an upper limit of 10% can be set on the enhancement in the CH$_4$ emission at $1233.455$ cm$^{-1}$ over the E site observed an hour before the HST/FOS spectra did.

FIG. 10. Same as described in the legend to Fig. 9 for Scan 31-22. LCM is 58° W.
p_0, we first searched for the value of ΔT_0, allowing us to reproduce the intensity of the C_2H_2 line. We then calculated the corresponding radiance for the CH_4 line and compared it with the maximum allowed (Fig. 18a). As expected, temperature profiles perturbed at levels that are too deep produce too much CH_4 emission. More surprisingly, profiles for which the temperature increase is confined to pressures less than ~5 μbar also yield too much CH_4 emission. This behavior results from the extremely rapid decrease of the C_2H_2 mole fraction and weighting function above the ~1-μbar region, more pronounced than for CH_4. Taking into account a 10% calibration uncertainty in the C_2H_2 enhancement, we conclude that only profiles with p_0 in the range 3 to 8 μbar can simultaneously match the intensity of the C_2H_2 line and induce a CH_4 line increase limited to less than 10%. We also tested our second class of temperature profiles in which temperature increases as a power n of 1/p above a pressure level p_1 (see Section 5). Again we find that only a limited range of pressure levels p_1, namely 6–20 μbar, allow us to match the C_2H_2 line intensity while not significantly enhancing the CH_4 line (Fig. 18b). All solution profiles are characterized by a temperature of 208 ± 2 K around 3 μbar, the region where most information is available. When calibration uncertainty is included, the error bars amount to ±7 K. The temperature increase at 3 μbar is then ΔT_1 = 37 ± 7 K.

The H site is visible on the same scan near the Eastern limb at an airmass of about 3 (Fig. 6). Fitting the C_2H_2 line with the same type of temperature profile requires that T_1 is 183 ± 5 K at 3 μbar, in excess of 12 ± 5 K of the nominal one. Besides calibration uncertainties, we included pointing uncertainties because of the less favorable geometry of the observations. Considering a ±0.5 possible error in the airmass, this uncertainty alone amounts to about ±4 K (already included in the total one). The spectrum calculated with this temperature profile is shown in Fig. 17.

(b) July 30 1994 UT: Site K + W

As discussed above, the same acetylene line seems to be enhanced by ~20% over the K + W site, observed 11 days after impact K and 8 days after impact W (Scans 30-14 and 30-15 shown in Figs. 7 and 8). The increase in the C_2H_2 column density required to reproduce this enhancement, assuming that the temperature profile is nominal, is ~4 × 10^{12} molecule cm^{-2} (deposited above the 10- or 100-μbar levels). This is about 4 times higher than the HST UV upper limit for the G impact (Atreya et al. 1995), which should be roughly of the same size as K. Summing over all pixels, we found that the total mass needed to explain this bright spot would be ~3 × 10^{13} g. This is about 6 times larger than predicted by Zahnle (1996) for a “large” impactor (10^{12} g). These differences however are not so
overwhelming that an interpretation through a C$_2$H$_2$ abundance increase should be readily ruled out. On the other hand, this interpretation would not explain why no enhancement in the C$_2$H$_2$ radiance is detected over the L and G sites (Fig. 8). The corresponding upper limit on the column abundance deposited by G or L above the 100-µbar level is $2 \times 10^{17}$ molecule cm$^{-2}$.

The C$_2$H$_2$ bright spot can alternatively be interpreted by slightly larger temperatures over the K + W site. Using a profile altered above $p_1 = 100$ µbar, a temperature of 181 ± 1 K at 3 µbar, i.e., an increase by 10 ± 1 K over nominal, is implied by the observations. This temperature goes up to 184 ± 1 K for a model with $p_1 = 10$ µbar. Such a small modification of the temperature profile is consistent with methane images recorded one day later, showing no contrast exceeding 10% (Scan 31-12 in Fig. 5).

(c) July 31 1994 UT: Complex R–Q2–Q1–B–N

Acetylene emission is higher by ~15% in the region of the R, Q2, Q1, B, and N impacts observed in Scans 31-21 and 31-22 (Figs. 9, 10). This enhancement may be interpreted as an increase in the C$_2$H$_2$ column density by $\sim 2.5 \times 10^{17}$ molecule cm$^{-2}$ above the 10-µbar level, yielding a total mass of $\sim 2 \times 10^{13}$ g over the complex. Alternatively, it can be explained with a temperature increase of 10.5 ± 1 K around 3 µbar, using a profile perturbed above $p_1 = 10$ µbar (8 ± 1 K if $p_1 = 100$ µbar).

A summary of the temperature perturbations inferred from the CH$_4$ and the C$_2$H$_2$ observations is given in Table II.

7. ANALYSIS OF HCN OBSERVATIONS

HCN emission was detected on all sites observed (Figs. 6–10). HCN, which was absent from Jupiter’s stratosphere prior to the impacts (Bézard et al. 1995), is a product of shock chemistry. It is expected to form in the dry jovian air shocked to temperatures higher than 1500 K, ejected with the plume above the atmosphere, and falling back 10–15 min after the explosions (Zahnle 1996). It is thus deposited in this reentry shock region where we also observed modifications of the thermal structure. In this region
FIG. 13. Spectra recorded on July 20, 08:57 UT (Scan 20-32) over the L site, the K site, and outside the impact sites (lines with squares) are compared with best fit synthetic spectra (thick solid lines). The observed spectra have been corrected for Doppler shift.

(10–100 μbar), the eddy mixing time is on the order of 1 or 2 years (Gladstone et al. 1996), i.e., much longer than our observation period at the IRTF.

We used these arguments as guidelines for modeling the observed HCN lines. First, we fixed the HCN mole fraction to zero below the level where the temperature model is perturbed. For models where we considered a constant temperature increase above a level $p_0$, we adopted a con-
FIG. 14. A comparison of the CH$_4$ spectrum observed over the L site (Scan 20-32; Col. 3, Row 3) with synthetic spectra calculated for temperature profiles perturbed above pressure levels of 0.01 (a), 0.1 (b), and 1 (c) mbar (see text). In all three cases, the constant perturbation is adjusted to reproduce the CH$_4$ line at 1233.455 cm$^{-1}$.

In each case, the temperature departure ($\Delta T_0$, above $p_0$, or $\Delta T_1$ at 3 $\mu$bar) is constrained by the simultaneous C$_2$H$_2$ observations. For each pixel, we first determined the temperature departure required to reproduce the C$_2$H$_2$ line intensity, and then the HCN column density from the HCN line intensity. The total mass of HCN is derived by summing the column density times the area sustained by each pixel.

(a) July 20 1994 UT: Sites E and H

Our nominal model yields a maximum HCN column density of $4.5 \pm 0.5 \times 10^{15}$ molecule cm$^{-2}$ for the E site (averaged over the four brightest pixels). The error bars account for the noise level and uncertainties in the continuum placement around the HCN line. The corresponding HCN mole fraction at 15 $\mu$bar is $1.4 \times 10^{-6}$ and increases with height as $p^{-0.5}$. The model that best fits the spectrum at the center of the impact site is shown in Fig. 17. Contributions from all pixels between Rows 3 and 15 were summed to derive a value of $0.95 \pm 0.1 \times 10^{12}$ grams for the E site. Emission from Rows 1 and 2 most likely originates from Impact A.

The same analysis for the H site (Rows 16 to 21) provides
a maximum HCN column density of \(2.7 \pm 0.3 \times 10^{15}\) molecule cm\(^{-2}\), about 40% lower than for Site E. Summing the contributions over all relevant pixels yields a mass of \(0.45 \pm 0.05 \times 10^{12}\) grams.

Larger systematic errors arise from assumptions in the model. Varying the HCN vertical distribution from a \(p^{-0.5}\) to a \(p^{-0.25}\) or a \(p^{-0.75}\) height dependence yields a \(\pm 20\%\) variation on the HCN mass for E (\(\pm 16\%\) for H). Varying \(p_1\) between 7 and 20 \(\mu\)bar has a dramatic \(+15/−50\%\) effect on the mass for E \((+10/−45\%\) for H). Alternative models with a constant temperature increase and uniform HCN mole fraction above \(p_0\) lead to HCN mass departures of \(+25/−45\%\) from the nominal model when \(p_0\) is varied between 3 and 7 \(\mu\)bar. Finally a 10\% uncertainty in the flux calibration induces an additional \(\pm 10\%\) uncertainty in the HCN mass for each site. Combining all error bars quadratically leads to masses of \(0.95 \pm 0.5 \times 10^{12}\) g on the E site, and \(0.45 \pm 0.2 \times 10^{12}\) g for the H site.

(b) July 30 1994 UT: Sites K + W and G + L

HCN emission on the K + W site was mapped in Scan 30-14 (Rows 7-21) (Fig. 7). Our nominal model for the big impact K assumes a HCN distribution extending down to 100 \(\mu\)bar. Attributing the \(\text{C}_2\text{H}_2\) intensity enhancement to a temperature increase from the more recent and smaller W impactor, we used a temperature model perturbed above \(p_1\) = 15 \(\mu\)bar as we did for the E and H sites. Solving simultaneously for the temperature departure and the HCN vertical profile, we inferred a column density \(\approx 1.4 \times 10^{15}\) molecule cm\(^{-2}\) at the impact center, corresponding to a mixing ratio of \(0.6 \times 10^{-6}\) at 100 \(\mu\)bar. Using the nominal temperature profile in the atmospheric model would yield a maximum column density 20\% higher. Model uncertainties were estimated by considering different vertical distributions for HCN: varying as \(p^{-0.25}\) or \(p^{-0.75}\) above 100 \(\mu\)bar, having cutoff pressure levels between 20 and 500 \(\mu\)bar, or constant above pressure levels in the range 8-40 \(\mu\)bar. In the error analysis, we also considered the nominal temperature profile, accordingly assuming that the \(\text{C}_2\text{H}_2\) enhancement was due to a real abundance increase. Summing the contributions from all pixels over the K + W site, a total mass of \(2.1^{+1.0}_{-0.6} \times 10^{12}\) g was derived.

HCN emission was also present over the L and G sites (Fig. 8, Rows 1–16). Because \(\text{C}_2\text{H}_2\) emission appears to be nominal over this area, we adopted the nominal temperature profile to model the HCN lines. We used a mixing ratio...
FIG. 16. Temperature profiles that fit the CH$_4$ lines observed on the L and K sites, respectively 11 and 23 hr after impact. This family of profiles have temperature increasing as a negative power of the pressure above a given level.

that increases with height as $p^{-0.5}$, following the analysis of the K + W site. A maximum column density equal to 1.2 $\times$ 10$^{16}$ molecule cm$^{-2}$ was found, corresponding to a mixing ratio of 0.5 $\times$ 10$^{-6}$ at 100 $\mu$mbar. Considering the same error sources as for the K + W analysis, we derived a mass of 3.9 $\pm$ 1.0 $\times$ 10$^{12}$ g for the observed area. In this scan, the western limb of the jovian disk was located at a longitude of 35°, while the G impact occurred at $\lambda$ = 26° (Hammel et al. 1995). Under the assumption of a spot size of ~30,000 km centered at 26°, we estimate that only 65 $\pm$ 20% of the G site was imaged in this scan. We then multiplied the above mass by 2/1.65 to get an estimate of the mass of the whole L + G complex, and derived a value of 4.8 $\pm$ 1.4 $\times$ 10$^{12}$ g.

(c) July 31 1994 UT: Complex G–Q–R–S

The large spot visible in the HCN images from Scans 31-21 and 31-22 at row numbers higher than 3 (Figs. 9, 10) is due to the impacts G, D, S, R, Q2, Q1, B, and N. We will hereafter refer to this complex as G–Q–R–S, i.e., retaining only the impacts of Class 1 or 2 (Hammel et al. 1995). We nominally interpreted the observed ~15% C$_2$H$_2$ enhancement as caused by higher temperatures likely resulting from the most recent Q1 and R impacts. We therefore employed a temperature model perturbed above $p_1 = 15$ $\mu$mbar as we did in the analysis of K + W. HCN is assumed to be present above the same pressure level $p_1$ at longitudes higher than 40°, i.e., for row numbers smaller than 16 (Scan 31-21) or 17 (Scan 31-22). For larger row numbers, the bigger G impact is likely to be the dominant source of HCN; we therefore used a HCN profile with a cutoff at 100 $\mu$mbar rather than 15 $\mu$mbar. The derived column density is maximum at the center of the Q1 impact, reaching ~0.7 $\times$ 10$^{16}$ molecule cm$^{-2}$. The corresponding mixing ratio is 2 $\times$ 10$^{-6}$ at 15 $\mu$mbar, increasing above as $p^{-0.5}$. Combining information from Scans 31-21 and 31-22, we obtained an integrated mass of 3.0$^{+1.0}_{-0.5}$ $\times$ 10$^{12}$ g for the longitude range 25°–90° (Rows 4–21). This range encompasses the Q, R, and S impacts as well as a fraction of the G site that we estimate to 50 $\pm$ 20%. Correcting for this fraction and assuming a mass for G half of that derived for L + G, we obtain a mass of 4.3 $\pm$ 1.3 $\times$ 10$^{12}$ g for the G–Q–R–S complex, or equivalently 1.9 $\pm$ 1.3 $\times$ 10$^{12}$ g for the Q–R–S complex alone.

Our HCN mass determinations are summarized in Table III. We observed longitudes covering all impact sites, excluding A and C. These two fragments are classified as 2a, as are E and H (Hammel et al. 1995). Images recorded at 7.75 $\mu$m indicate that, about 4 hr after impact, the stratospheric heating produced by A and H was about the same...
Fig. 17. Spectra recorded on July 20, 06:14 UT over the E site, the H site, and outside the impact sites (lines with squares) are compared with best fit synthetic spectra (thick solid lines). The nominal temperature profile (Fig. 11) was used in the calculations outside the impacts. On the impact sites, the temperature model departs from the nominal profile above the 15-μbar level, reaching a temperature of 182 K for H and 208 K for E at 3 μbar. An HCN mole fraction of $1.4 \times 10^{-6}$ at 15 μbar, increasing with height as $1/\sqrt{p}$, was used for the E and H spectra. The observed spectra have been corrected for Doppler shift.
FIG. 18. (a) Solid line: Plot of the temperature increase $\Delta T_0$ as a function of the cutoff pressure level $p_0$ needed to reproduce the $C_2H_2$ line enhancement for Site E (July 20, 06:04 UT). The perturbation $\Delta T_0$ is assumed to be constant above $p_0$. Dashed line: Ratio of the $CH_4$ line intensity for the perturbed temperature profile to that for the nominal profile as a function of $p_0$. The horizontal long-dashed line sets the upper limit consistent with the $CH_4$ spectral image from Scan 20-15. Models with $p_0$ between 3 and 8 $\mu$bar are consistent with the observations. (b) Same as (a) for a second class of smoother temperature models in which temperature departs from the nominal profile at a pressure level $p_1$, varying above as $p^{-n}$. $\Delta T_1$ denotes the temperature increase at the 3-$\mu$bar level with respect to the nominal value of 171 K. Models with $p_1$ lying between 6 and 20 $\mu$bar are consistent with the observations.
(Livengood et al. 1995), suggesting that they had similar masses. A reasonable guess of the HCN mass produced in A and C may be \(1.0 \pm 0.4 \times 10^{12}\) g, i.e., about twice that produced by H. This number is also about half of the mass found in Q–R–S. We then estimated the total mass of HCN produced by all impacts (A–W) and found \(1.1 \pm 0.4 \times 10^{12}\) g. Here we added the errors from our different observations, because most of these are systematic and do not add quadratically.

8. DISCUSSION

(a) Temperature

Simultaneous analysis of strong and weak CH\(_4\) lines clearly shows that the stratospheric heating induced by the impacts over areas 15,000 km wide or larger was confined to upper atmospheric levels. For the L site observed 11 hr after impact, the temperature increase did not exceed 20 K below 1 mbar (less than 10 K below 10 mbar) (Fig. 15), whereas it reached \(~80\) K in the 5-\(\mu\)bar region. Models in which temperature is uniformly increased above a given pressure level require that this level is no deeper than 40 \(\mu\)bar. Smoother temperature models with a constant lapse rate set above a pressure level \(p_1\) can also reproduce the CH\(_4\) observations, provided that \(p_1\) is less than 500 \(\mu\)bar. Figure 19 shows profiles of this type (with \(p_1 = 100\) \(\mu\)bar) inferred for the L and K sites.

It should be noted that similarly the brightening seen over the impact sites in thermal images around 7.7 \(\mu\)m (Billebaud et al. 1995, Livengood et al. 1995, Orton et al. 1995) results from enhanced CH\(_4\) emission originating higher than the 500-\(\mu\)bar level. It is thus incorrect to ascribe the corresponding temperature enhancement to the region around 10 mbar, despite the fact that weighting functions peak there (Fig. 12).

Heterodyne observations of rotational HCN and CO lines at the G impact site show that these species were only present above the 300- (CO: Lellouch et al. 1995, Lellouch 1996), or 500-\(\mu\)bar levels (HCN: Marten et al. 1995). On the other hand, their vertical distribution must extend down to at least the region 50–100 \(\mu\)bar to reproduce the width of the lines, larger than that expected solely from Doppler broadening and velocity smearing. Upwelled parcels of jovian and cometary air are expected to deposit both their energy and the compounds formed by shock chemistry in the region of the reentry shock. Numerical simulations indicate that the lower boundary of the fallen plume (where the ejecta are deposited) is mostly in the range 10–100 \(\mu\)bar for a big impact (Zahnle and Mac Low 1995, Zahnle 1996). Our finding that temperature perturbations were confined above the 500-\(\mu\)bar level is thus consistent with models of the ejecta plume reentry and with heterodyne observations of molecules formed by shock chemistry.

Methane band observations of the L and K sites were also performed with the MIRAC2 camera at the IRTF using a narrow filter (2\%(Livengood et al. 1995). A reanalysis of the MIRAC2 images shows that the radiance over the L site was 2–3 times higher than the surroundings 4 hr after impact, and about 40\% higher 3 hr after impact. The K site showed a 35\% excess emission 43 hr after impact. We attempted to compare Irshell results with MIRAC2 observations by calculating the excess radiance expected in the MIRAC2 filter using the temperature models we inferred. We found 7.85-\(\mu\)m radiances amounting to 2.2 times the nominal one for L observed 11 hr after impact, and to 1.3 times nominal for K observed 23 hr after impact. We conclude that the two data sets do not show any major inconsistency, considering the uncertainties in the flux calibrations.

Observations of CO emission lines at 4.7 \(\mu\)m over the L site 4.5 hr after impact indicate temperatures around 275 K in the plume (Maillard et al. 1995, Brooke et al. 1996). This temperature pertains to the \(~10^{16}\) CO molecule cm\(^{-2}\) level. The corresponding atmospheric level obviously depends on the actual vertical profile of CO in the plume of

### TABLE II

<table>
<thead>
<tr>
<th>Site</th>
<th>Time elapsed since impact (days)</th>
<th>Temperature increase (K)</th>
<th>Pressure level ((\mu)bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>+0.9</td>
<td>30 ± 5</td>
<td>10</td>
</tr>
<tr>
<td>L</td>
<td>+0.4</td>
<td>80 ± 10</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>+2.6</td>
<td>&lt;10</td>
<td>10</td>
</tr>
<tr>
<td>H</td>
<td>+1.4</td>
<td>12 ± 5</td>
<td>3</td>
</tr>
<tr>
<td>W</td>
<td>+8.8</td>
<td>&lt;10</td>
<td>10</td>
</tr>
<tr>
<td>O1</td>
<td>+10.4</td>
<td>~13(^{a})</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^{a}\) Observations can alternatively be interpreted by an increase in the \(\text{C}_2\text{H}_2\) column density of \(~4 \times 10^{17}\) molecule cm\(^{-2}\).

### TABLE III

<table>
<thead>
<tr>
<th>Site</th>
<th>Column density (molecule cm(^{-2}))</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>0.45 ± 0.2 (\times 10^{16})</td>
<td>0.95 ± 0.5 (\times 10^{12})</td>
</tr>
<tr>
<td>H</td>
<td>0.27 ± 0.1 (\times 10^{16})</td>
<td>0.45 ± 0.2 (\times 10^{12})</td>
</tr>
<tr>
<td>K + W</td>
<td>1.4 (\times 10^{16})</td>
<td>2.11 (\times 10^{12})</td>
</tr>
<tr>
<td>L + G</td>
<td>1.2 (\times 0.3 \times 10^{16})</td>
<td>4.85 ± 1.4 (\times 10^{12})</td>
</tr>
<tr>
<td>G–Q–R–S</td>
<td>0.7 (\times 0.3 \times 10^{16})</td>
<td>4.3 ± 1.3 (\times 10^{12})</td>
</tr>
<tr>
<td>All (A–W)</td>
<td>1.1 (\times 0.4 \times 10^{13})</td>
<td>1.1 ± 0.4 (\times 10^{13})</td>
</tr>
</tbody>
</table>
FIG. 19. Temperature profiles derived from the analysis of CH$_4$ lines (K and L sites) and C$_2$H$_2$ lines (E and H sites) recorded on July 20 1994 UT. Error bars at the probed levels are indicated. The thick solid line is the nominal temperature profile outside of the impacts. Also indicated is the temperature determined from observations of CO lines at the L site, 4.5 hr after impact (Maillard et al. 1995).

which little is known. Lellouch et al.’s (1995) profile leads to a pressure level of 2 $\mu$bar. At this level, the temperature in our model of the L site lies between 270 and 320 K, including all uncertainties. This is consistent with the temperature derived from the CO lines. However, the large uncertainty on the CO vertical profile precludes any stringent constraints: temperature perturbations half or twice those derived probably could be accommodated with the CO data (Fig. 19). One would further expect temperatures to be higher 4.5 hr after impact than when we observed, 11 hr after impact. Maillard et al.’s analysis also concluded that a strong positive lapse rate, at least 30 K over two CO pressure decades, probably exists within the plume. Temperatures lower than 245 K near the base of the plume (100 $\mu$bar) are quite consistent with our model profiles in which temperature rapidly increases upward above a given $p_1$ ($p_1 < 500$ $\mu$bar).

The E site was imaged with Irshell 2.6 days after impact. The fact that E is very bright in the C$_2$H$_2$ image and not visible in the CH$_4$ image carries valuable information on the location of the atmospheric heating. Models in which temperature is uniformly increased above a pressure level $p_0$ require that this level is in the range 3–8 $\mu$bar. Smoother temperature models with a constant lapse rate set above a pressure level $p_1$ also reproduce the observations, provided that $p_1$ is located between 6 and 20 $\mu$bar. Figure 19 shows the profiles we inferred for the E and H sites with $p_1 = 15$ $\mu$bar as observed on July 20 1994 UT. The E site is detected in the C$_2$H$_2$ image and not in the CH$_4$ because the C$_2$H$_2$ profile extends higher in the stratosphere than the CH$_4$ profile. Our results are thus sensitive to the vertical distributions we assumed for these two compounds, based on the photochemical model by Gladstone et al. (1996). On the other hand, it should be noted that if the acetylene and methane profiles had similar vertical distributions, it would be impossible to reproduce the enhancement observed for the C$_2$H$_2$ line without producing a similar enhancement in the CH$_4$ strong line.

E was a smaller fragment than L or K. This is attested by the smaller amount of HCN produced and by the weaker lightcurve generated by the reentry shock (e.g., Lagage et al. 1995). Models of the dynamics of the ejecta plumes predict that the pressure of the reentry shock is proportional to the mass of the fragment (Zahnle and Mac Low 1995). The temperature increase due to this shock is thus expected to take place at higher levels for E than for L, in agreement with the present analysis.

Observations of the E site with the MIRAC2 camera equipped with the 7.85-$\mu$m filter indicate a $\sim$45% increase in the brightness with respect to its surroundings 12.5 hr
after impact. The site was indistinguishable from the surroundings 3.5 days after impact, with a maximum allowable excess radiance of \( \approx 5\% \). We calculated that Irshell observations of the C\(_2\)H\(_2\) line 2.6 days after impact would yield a 10% increase in the 7.85-\(\mu\)m flux, which fits into the two MIRAC2 data points.

We found that the temperature increase needed to reproduce the C\(_2\)H\(_2\) line intensity over the H site was \( \approx 3 \) times smaller than for the E site, despite the fact that it were heavier than \( 10^{14} \) g. A recent analysis of the CO line, 0\(\rightarrow\)0 from chemical kinetics models of the plumes, but not by calculations by Lyons and Kansal (1995) indicate that essentially all of the methane is converted to acetylene in the jovian air that is shocked at \( T \approx 1700 \) K during the explosion phase. According to Zahnle’s simulations, about 10 times the mass of the fragment is shocked above this temperature; the mass of C\(_2\)H\(_2\) produced by a \( 10^{14} \) g fragment would then be \( \approx 4 \) times lower than we would need for K + W. It is in fact possible that the largest fragments were heavier than \( 10^{14} \) g. A recent analysis of the CO millimeter observations at the K site yields a CO mass \( \approx 1.5 \times 10^{14} \) g (Lellouch et al. 1996). Chemical models predict that this amount is produced by a fragment having a mass in the range \( 2\times10^{14} \) g, depending on the O/C ratio in the comet (Zahnle 1996). Such fragments would generate quantities of acetylene that are close to that needed to reproduce the enhancement of the C\(_2\)H\(_2\) line over the K + W and Q1 sites using a nominal temperature profile.

However, we note that there was no detectable enhancement of the same C\(_2\)H\(_2\) line over the G and L sites, which is consistent with the upper limit derived from UV spectroscopy (Atreya et al. 1995). We thus tend to regard a true C\(_2\)H\(_2\) enrichment as a less likely possibility because it would imply that detectable amounts of C\(_2\)H\(_2\) were produced over K + W and Q1 and not over L and G. Because the mass of C\(_2\)H\(_2\) produced is proportional to the mass of the impactor, one expects similar amounts over the L, G, and K sites, contrarily to observations.

(c) Thermal Energy

The temperature enhancements observed over large areas several hours after the impacts show that the energy of the plumes was partly transferred to the jovian atmosphere, and not immediately radiated away. Our results can be used to estimate the amount of thermal energy stored in the jovian atmosphere. This energy \( E \) is given by:

\[
E = C_p S H_0 \frac{n_0}{p_0} \int_{p_{\text{min}}}^{p_1} \Delta T(p) \, dp,
\]

where \( C_p \) \( (\approx \frac{3}{2} \, k) \) is the molecular specific heat of the atmosphere, \( S \) is the area over which the thermal perturbation takes place, \( H_0 \) is the atmospheric scale height at standard temperature \( T_0 \), \( n_0 \) is the atmospheric number density at pressure \( p_0 \) and temperature \( T_0 \), and \( \Delta T(p) \) is the temperature increase extending between pressure levels \( p_{\text{min}} \) and \( p_1 \).

We estimated this energy for impact sites L and K observed 11 and 23 hr after collision respectively. As a baseline, we used temperature models perturbed above \( p_1 = 100 \) \(\mu\)bar because, as discussed above, millimeter observations of CO for large impacts indicate a cutoff pressure at this level (within about a factor of 2) (Lellouch et al. 1996).
We considered as extreme cases models with \( p_1 = 30 \) and 300 \( \mu \text{bar} \). Calculations then yield \( E = 3 \times 10^{25} \) erg for the L impact site, and \( 2 \times 10^{26} \) erg for our observations of the K site. We can now compare these results with the estimates for the energy transported in the plumes.

Assuming that the K and L fragments had a mass between 1.5 and \( 4 \times 10^{14} \) g (Lellouch et al. 1996), their kinetic energy was on the order of 2.5 to \( 7 \times 10^{27} \) erg. According to Zahnle and Mac Low (1995)’s simulations, \(~40\%\) of this energy is invested in the ejecta plumes. Using Zahnle (1996)’s mass–velocity distribution for the ejected gas, we found that about \(~40\%\) of the energy of the plume is deposited at altitudes above the \(~100-\mu\text{bar}\) level, the region where we measured the temperature enhancements using the strong CH\(_4\) lines. The rest of the energy is carried by particles which do not have enough velocity to reach this pressure level, and do not affect the temperature structure of the lower stratosphere in a detectable way. The energy transported above the \(~100-\mu\text{bar}\) level by the K or L plumes is then on the order of \( 0.8 \pm 0.4 \times 10^{27} \) erg. The thermal energy we determined for the upper stratosphere of Jupiter over the L site is about \(~40\%\) of this quantity. This thermal energy was most likely larger \(~1\) hr after the L impact, just after the plume had spread horizontally, than \(~1\) hr after when we observed. An energy loss of \(~40\%\) appears as a reasonable estimate, as this is about the difference observed between the L and the K impacts observed \(~12\) hr apart. It is also consistent with the \( 1/e \) time constant of \(~20\) hr for the decay of the 7.85-\( \mu \text{m} \) excess flux of the L site in the MIRAC2 images. We then find that between \(~20\) and \(~100\%) of the plume energy was transferred and stored in the jovian atmosphere, with a preferred number of \(~60\%\).

The thermal energy derived here implies that not all of the plume energy was radiated away immediately, contrary to what is usually assumed (e.g., Zahnle 1996). A significant fraction was instead used to heat the jovian atmosphere over an area larger than \(~15,000\) km. Energy could have been transferred when the reentering plume shocked and compressionally heated the jovian atmosphere (K. Zahnle, private communication). A second opportunity was provided when the horizontal motion of the plume was slowly damped in Jupiter’s atmosphere. The energy of horizontal motion still present after the shock is a significant fraction of the total energy of the plume. It dissipates more slowly than that of the vertical motion, material is less heated, and radiative cooling is less efficient as attested by the thermal lightcurves (Lagage et al. 1995). Friction probably allows for a significant transformation of this energy into heating of the jovian atmosphere.

\[ (d) \text{Hydrogen Cyanide} \]

Our analysis indicates that \(~2-2.5 \times 10^{12} \) g of HCN were produced by the largest fragments (Class 1) (G, K, L), and about \(~2-4\) times less by Class 2 fragments (Table III). The integrated mass produced by all impacts is estimated to be \(~1.1 \pm 0.4 \times 10^{13} \) g. Column densities \(~\approx 1.2 \times 10^{16} \) molecule \( \text{cm}^{-2} \) are found for Class 1 impacts, and \(~2-3\) times less for Class 2 impacts.

Marten et al. (1995) presented an analysis of millimeter lines of HCN recorded on July 19, 1994 at the James Clerk Maxwell Telescope on the location of the G impact. Assuming a uniform distribution of HCN above the 0.5-mbar level, they derived a column density of \(~3 \times 10^{15} \) molecule \( \text{cm}^{-2} \), i.e., \(~4\) times less than our inferred value. Assuming an emitting area of \(~4^\circ\), a total mass of \(~6 \times 10^{11} \) g was derived, again \(~4\) times less than we measure. However, the inferred HCN abundance strongly depends on assumptions on the vertical profile of this gas, and higher values can be accommodated by the data (Marten et al. 1995). For example, if HCN is confined to pressure levels less than \(~0.1 \) mbar, millimeter lines indicate a column density of \(~1.2 \times 10^{16} \) molecule \( \text{cm}^{-2} \), in excellent agreement with the Irshell data (A. Marten, private communication).

Hydrogen cyanide is expected to form in the dry jovian air shocked at temperatures larger than \(~1500\) K (Zahnle 1996). Production in the plume from the cometary material itself is predicted to be negligible, provided that the comet’s O/C ratio is larger than 1. Zahnle’s model of shock chemistry predicts that a \(~10^{14} \) g fragment produces an HCN mass of \(~2 \times 10^{12} \) g, in agreement with what we determined for the biggest impacts (the mass of HCN produced is proportional to the mass of the fragment). However, as discussed above, it is likely that the largest fragments had a mass on the order of \(~2-3 \times 10^{14} \) g, rather than \(~10^{14} \) g. Along the same line, Zahnle’s calculations predict that a mass of \(~6 \times 10^{14} \) g for all fragments is enough to account for the total mass of HCN we determined (\(~1.1 \pm 0.4 \times 10^{13} \) g). This is about half of the actual mass of the parent body as estimated from tidal disruption models (Asphaug and Benz 1994, Solem 1994). Models of shock chemistry thus seem to produce slightly more HCN than observed. As suggested by Zahnle (1996), it is possible that a significant fraction of the HCN actually ends up as more complex nitriles or as particulates. In any case, the fact that predictions agree with observations well within an order of magnitude is quite satisfactory, regarding the complexity of these simulations and the unknowns in the chemical processes.

Irshell observations conducted in May 1995 at the IRTF showed that HCN was still present in large amounts at southern latitudes, having significantly spread outward of the impact latitude (Griffith et al. 1995). A preliminary analysis of these data indicates a total mass of \(~1 \times 10^{13} \) g, similar to what we derived from the July 1994 data (Table III). A more refined analysis, currently in progress, is required to assess whether a slight change can be detected. The lifetime of HCN in the jovian stratosphere is
likely to be governed by vertical mixing and should therefore exceed a year (Marten et al. 1995). Its abundance is then expected to be about the same 10 months after the collision, except if some is produced from photochemistry of N-compounds over the impact sites as suggested by some recent modeling (Moses et al. 1995).

(e) Variability of the Impact Plumes

Models of the dynamics and chemistry of the impact plumes (Zahnle and Mac Low 1994, Zahnle 1996) predict that the pressure levels of the reentry shocks, the lightcurves then produced, and the mass of compounds formed by shock chemistry should all be proportional to the mass of the fragment. Although our data indicate that Class 1 fragments did produce deeper temperature enhancements and more HCN than Class 2 fragments, a more detailed intercomparison of our results shows a more subtle behavior.

The infrared luminosity of the so-called main event for the L plume was about 4 times larger than that of the H event (Lagage et al. 1995). We accordingly found that the amount of HCN present over the L site was about 4 times that over the H site (Table III). In contrast, the H plume radiated about twice as much energy as the E plume during the atmospheric reentry (Lagage et al. 1995), while the mass of HCN produced by H is about half that produced by E. We also found that the E site was hotter than the H site around 3 μbar on July 20 UT, albeit older (2.6 vs 1.4 day). This would suggest that either E was more energetic than H or that it lost its energy less efficiently. In the same vein, Livengood et al. (1995) noticed that the temperature perturbations were similar over the A and H sites, which seems to imply that the two fragments had about the same energy, while the infrared luminosity of the H event was twice that of A. It thus appears that the H plume was surprisingly luminous with regard to its energy, reflected in the HCN produced and in the heating of the jovian stratosphere.

We suggest here that this behavior may reveal some variability in the plume composition among the various impacts. The luminosity of the plume is not strictly speaking proportional to its mass, but rather to the mass of the radiating material, likely to be predominantly dust particles. This is supported by the good correlation between the relative luminosity of the plume fallbacks (Lagage et al. 1995, Meadows et al. 1995) and the optical depth of the dust left over the impact sites (West et al. 1995). The differences in the luminosity, the amount of HCN produced, the stratospheric heating, and its evolution with time can then be understood if the E plume was more massive than H but had a lower dust content, i.e., a lower dust/gas ratio. From the limited set of observations we have, we would then conclude that the H and L plumes (which exhibit a similar ratio between luminosity and HCN mass) were dustier than E and A (considering Livengood et al.’s observations). This variability could originate either from a real heterogeneity of the comet fragments, or from a difference in the way the ejecta plumes were formed during the explosions in the jovian troposphere.

REFERENCES


