GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 12, PAGES 1573-1576, JUNE 15, 1995

Methane and carbon monoxide infrared emissions observed at the Canada-France-Hawaii Telescope during the collision of comet SL-9 with Jupiter

J.-P. Maillard[1,6], P. Drossart[2,6], B. Bézard[2,6], C. de Bergh[2], E. Lellouch[2], A. Marten[2], J. Caldwell[3,6], J.-C. Hilico[4], and S.K. Atreya[5]

Abstract. Observations with the Fourier Transform Spectrometer were conducted in spectral ranges from 1.6 to 4.7 μm, from July 17 to 21 (UT) on the hot plumes appearing on the limb as well as hours or days after the impacts. We present here an analysis of the methane emission observed at 3.3 μm some 10 min after the C impact, indicating the presence of a very small (less than 100 km wide) hot region with temperatures in the 750–1500 K range within the 0.1– to 0.01–mbar region. We also report the detection of CO emission at 4.7 μm 4.5 hrs after the L impact, indicative of a temperature of 274$\pm$10 K at the $\sim 10^{16}$ CO molec cm^{-2} level. The observations suggest that the stratospheric temperature decreases with depth by at least 30 K over two CO pressure decades.

Observing conditions

The Fourier Transform Spectrometer (FTS) on the 3.6-m Canada–France–Hawaii Telescope (Mauna Kea, Hawaii) participated in the exceptional campaign for observing the crash of comet Shoemaker-Levy 9 on Jupiter by being scheduled from July 17 to July 21 (UT), 1994. For each observation, a 2.5-arcsec circular aperture, corresponding to a projected diameter of 9400 km at Jupiter, was centered on an impact site and kept accurately on this position by offset-guiding from a galilean satellite.

Table 1 summarizes the observations which were conducted. Beside a filter centered at 4.7 μm (2080–2180 cm^{-1}) well suited to detect CO, three other filters were used, around 3.3 μm (2850–3050 cm^{-1}) for CH_4, 2.3 μm (4100–5200 cm^{-1}) and 1.6 μm (5400–6800 cm^{-1}). In each filter, spectra of Vega were recorded several hours after the Jupiter observations at similar airmasses to correct for instrumental response and telluric opacity, and to provide absolute flux calibration.

Five sites (B, C, G, L and R) were observed at 4.7 μm, G being observed twice with a one day interval. CO was detected in emission on the L site (and only there) 4h30 after impact. Concommitant observations at the United Kingdom Infrared Telescope [*Brooke et al.,* 1994] confirm this detection. It is noteworthy that no CO emission was seen on the G site one day after the impact, probably due to the rapid cooling of the stratosphere. C and R impacts were observed just a few minutes after the explosion, in the 3.3-μm filter. For both impacts, when the plume became visible at Jupiter's limb, a strong emission was seen centered at $\sim$ 3000 cm^{-1}, which corresponds to the Q branch of the ν_3 band of methane. A modelling of this emission is presented here. Methane emissions on impacts R and W were reported at 7.8 μm [*Sprague et al.,* 1994; *Bjoraker et al.,* 1994], and, on impact H, over a small spectral range near 3.53 μm, at the edge of the range observed with the FTS [*Encrenaz et al.,* this issue].

CH_4 emission at impact C

Spectra of the 3.3–μm CH_4 emission were recorded with an integration time of 5 min for impact C. To enhance the signal–to–noise ratio, the spectral resolution was degraded to 1.7 cm^{-1}, corresponding to an effective integration time of 38 sec. Figure 1 shows the spectrum at impact C, which exhibits the strongest emission feature at 3001 cm^{-1}. Similar spectra were obtained for impact R, fainter than on impact C. We focus here on the impact C spectrum. A good fit with pure methane emission is obtained only when re–absorption of hot methane emission is allowed in the cold atmosphere of Jupiter. The timing of the observation (maximum emission on 17:07:20 UT), compared to the geometry of the impacts on Jupiter [*Chodas and Yeomans,* 1994] implies that the observations occured at very large emission angles. An emission angle of 90° (known only to 5° because of the uncertainty on the impact time) is assumed in the model, with full account of the spherical geometry in the radiative transfer.

[1] Institut d'Astrophysique de Paris, CNRS, France

[2] Département de Recherche Spatiale, CNRS-URA264, Observatoire de Paris, Meudon, France

[3] Physics Department, York University, North York, Canada

[4] Laboratoire de Physique de l'Université de Bourgogne, Dijon, France

[5] Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, USA

[6] Visiting astronomer at the Canada-France-Hawaii Telescope operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France, and the University of Hawaii

Paper number 95GL01019
0094-8534/95/95GL-01019$03.00

Table 1. FTS OBSERVATIONS OF SL9/JUPITER

Frag.	Observation[a]	Range (cm^{-1})	Resolution
B	17:04:58 05:48	2080–2180	2.5×10^4
C[b]	17:06:53 07:52	2850–3050	1.4×10^4
	17:07:59 08:51	2080–2180	2.5×10^4
E	20:06:31 06:50	5400–6800	2.1×10^4
G	19:06:39 07:11	2080–2180	2.5×10^4
	19:07:28 07:55	4100–5200	1.5×10^3
	20:03:21 04:22	2080–2180	2.5×10^4
H	19:08:01 08:50	4100–5200	1.5×10^3
K	21:06:53 07:57	5400–6800	2.1×10^4
L	20:02:44 03:16	2080–2180	2.5×10^4
R[c]	21:05:36 05:52	2850–3050	1.0×10^4
	21:06:33 06:48	2080–2180	2.5×10^4
	21:07:04 07:26	5400–6800	2.1×10^4

[a]start dd:hh:mn end hh:mn (UT)
[b]observed in real time; max of CH_4 emission at 17:07:20
[c]observed in real time; max of CH_4 emission at 21:05:44

The hot emission is assumed to originate from an isothermal volume, at temperature T, located at a mean pressure P, with a vertical extension H and an horizontal extension D. H is assumed to be comparable to the unperturbed atmospheric scale height, *i.e.* about 25 km in the high stratosphere. Since the intensity of the emission strongly depends on temperature, this is equivalent to assuming that a region having the maximum temperature over one scale height altitude range mainly contributes to the observed emission. The free parameters of the model are therefore D, T and P. Outside the hot region, the atmosphere is supposed to keep its nominal temperature profile, taken from [*Gladstone and Skinner,* 1989], which at high altitudes is nearly isothermal with a temperature around 170 K. The methane vertical profile is taken from the same reference, with a tropospheric abundance around 0.2%. In the hot region, the methane mixing ratio has been decreased by a factor of two to roughly take into account the mixing of the cometary, methane–free material, with the atmosphere of Jupiter. Calculations were performed for pressure levels P between 1 mbar and 1 μbar and temperatures between 500 to 2000 K. Jupiter's atmosphere is very transparent at these altitudes, most of the haze absorbing at higher pressures, and gaseous opacity of methane must be the dominant absorption in this range. Other hydrocarbons have absorption bands near 3.3 μm, but their column density is 10^{-4} to 10^{-6} that of methane. Therefore, calculations with only methane lines were performed, including high J values (up to J=25) as well as the hot bands of CH_4 present in the range. More than 40,000 lines were included from a theoretical model by [*Hilico et al.,* 1994]. In addition to the methane lines, a small continuum was added, which may describe the emission of the heated dust in the fireball. This continuum is added mainly for consistency with the model used in [*Encrenaz et al.,* this issue], where such a continuum was found to be present.

The strong telluric methane absorptions present in the spectral range complicate the comparison between synthetic and observed spectra. Thanks to the Doppler shift of Jupiter (0.169 cm^{-1} in the spectrum of Fig. 1), the Jovian emission is still observable from the ground, but strongly perturbed, even at medium spectral resolution. Since division by a star spectrum at high resolution is not possible, because of the large number of strongly saturated lines in both spectra, the data are instead compared by multiplying the synthetic spectrum (shifted by the Doppler shift of Jupiter) by the star spectrum at high spectral resolution, and then by convolving the resulting spectrum to the resolution of the Jupiter spectrum. The normalization is obtained from the magnitude of the star, and allows us to convert the synthetic spectrum into the original instrumental units (Fig. 1).

A fit to the spectra is found for pressure levels $10^{-5} < P < 10^{-4}$ bar and temperatures $750 < T < 1500$ K. The influence of pressure and temperature variations is different on the spectral shape in the range 2850–2950 cm^{-1} (P branch), 3000 cm^{-1} peak and 3008 cm^{-1} secondary peak, giving the above constraints on P and T. Then, the absolute flux calibration from the Vega spectra allows an estimate of the size of the emitting

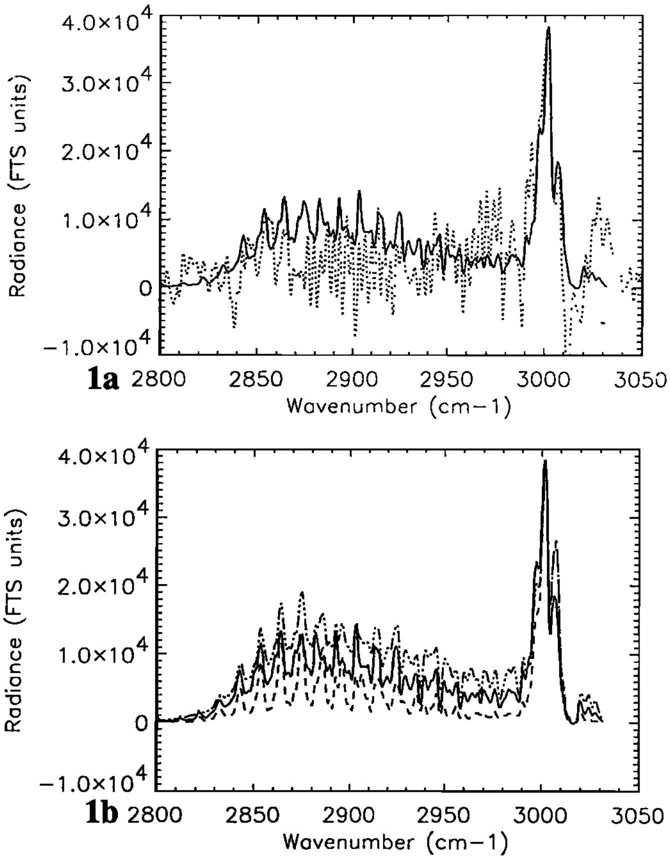

Figure 1. Spectrum of impact C on July 17:07:20 UT, at a resolution of 1700 (dotted line); the S/N ratio is about 10; the intensity is in original instrumental counts. The solid line is the best fitting model, with parameters: P=10^{-4}bar, T=1000 K, D=50 km; the peak spectral radiance near 3002 cm^{-1} is about 5×10^{-9} W $cm^{-2}sr^{-1}/cm^{-1}$.

region. The vertical size being assumed to be roughly 25 km, the horizontal dimension is found to lie between 20 km (for the highest temperature) and 100 km (for the lowest temperature). The emitting area is therefore very small compared to the aperture (9400 km wide). Nevertheless, it must be emphasized that these results rely on several assumptions. Improvements will come from a comparison with data from other observations

CO emission at Impact L

The 4.7–μm spectrum recorded on the L site, 4.5 hrs after the impact, consists of two components: thermal emission originating from Jupiter's troposphere at pressure levels of a few bars, and CO emission from the stratosphere locally heated by the impact (Fig. 2). Twelve individual lines from the (1–0) band of ^{12}CO are detected above the 3σ level (P2, P4, P7–P12, R2, R3, R5, R6). The weighted–averaged intensity of the P1–P12 and R1–R7 lines is found to be 0.113±0.006 erg $s^{-1}cm^{-2}sr^{-1}/cm^{-1}$ with an additional 20% uncertainty from the flux calibration. The corresponding brightness temperature is 222±3 K. Individual lines from the ^{13}C isotope are within the noise. However, averaging the observed radiances for the nine most intense lines in the bandpass (R2-R7, R9–R11) yields a mean line intensity of 0.019±0.008 erg $s^{-1}cm^{-2}sr^{-1}/cm^{-1}$, indicating a marginal detection of an emission from ^{13}CO at the 2.5–σ confidence level.

While the thermal background from the deep troposphere covers the 2.5–arcsec field of view, CO emission is limited to the area of the L site. To analyze these data, we assumed that the L impact site filled half the area of the field of view at the time of the observations. This would correspond to a 14000–km broad region on Jupiter's disk (7000–km in the projection), consistent with 10–μm images of the L site, 2 hr after the collision [*Lagage et al.,* 1994].

Observations were modelled by means of standard radiative transfer calculations. The temperature model outside of the impact site is taken from [*Griffith et al.,* 1992]. It pertains to cold regions of the STZ. Over the L site, two modifications were brought to this model above the 0.3–mbar level: the temperature was increased above its nominal ≈170 K value as a consequence of energy deposition from the impact, and the CO mixing ratio was increased above its tropospheric value of $\approx 1\times10^{-9}$. In a first step, we used the CO mixing ratio profile (4×10^{-5} at pressure levels higher than 0.3 mbar) derived by [*Lellouch et al.,* 1994] from millimeter observations of the G impact site, approximately 10 hours after impact. The lines are then optically thick and emission from ^{12}CO is formed near the $\sim10^{16}$ CO molec cm^{-2} level (p~2 μbar). ^{13}CO emission originates from ~100 times denser levels, assuming a terrestrial $^{12}C/^{13}C$ ratio. The intensities of the ^{12}CO lines can be reproduced adopting a uniform temperature of 267 K above the 0.3–mbar level. However, the model would then predict intensities for the R2–R12

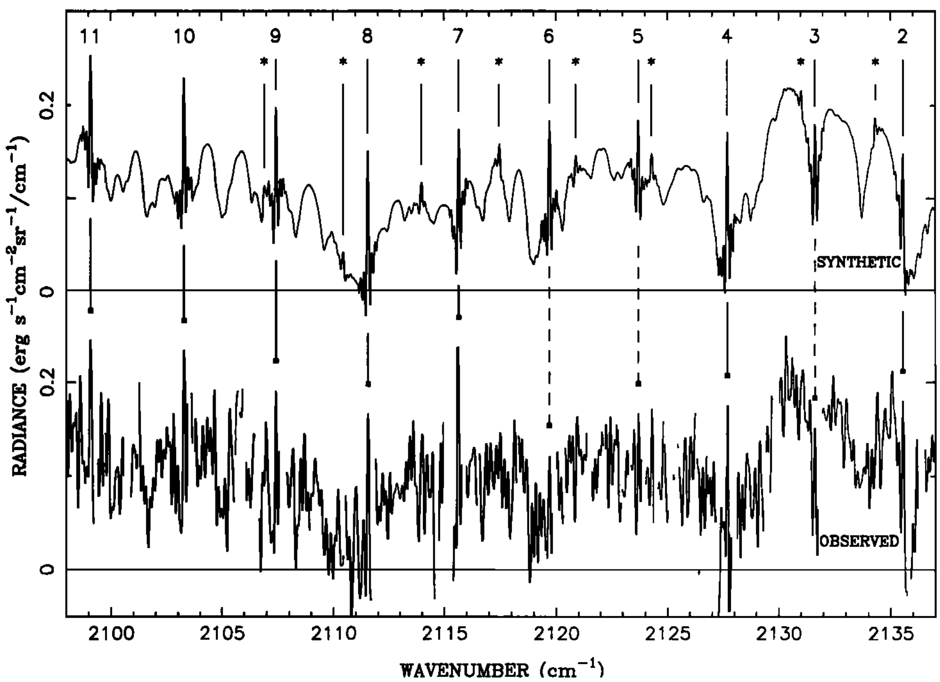

Figure 2. Portion of the 4.7–μm spectrum of the L site recorded 4.5 hrs after the impact at a resolution of 0.08 cm^{-1}. Data corresponding to regions where the telluric transmission is less than 0.50 are not plotted. The 1σ noise level varies between 0.02 and 0.04 erg $s^{-1}cm^{-2}sr^{-1}/cm^{-1}$. Many emission lines from the P–branch of the (1–0) band of ^{12}CO, marked with their rotational number, are detected with a S/N ratio higher than 3 (solid lines). Lines from the ^{13}CO isotope (indicated as $*$) are below the 3σ level. The best fit synthetic spectrum, assuming an isothermal CO layer at 274 K(see text), is shown for comparison.

^{13}CO lines about half those of the ^{12}CO lines, in conflict with the observations. This conflict can be resolved in two ways: either by decreasing the CO column density to reduce the line optical depths, or by assuming a temperature gradient within the region where CO is present.

In the first hypothesis, where an isothermal profile is adopted within the plume, we find that a CO column density equal to $1.5\pm0.8\times10^{17}$ molec cm^{-2} is needed to simultaneously reproduce the ^{12}CO and ^{13}CO emission. The corresponding mass of CO is then $1.0\pm0.5\times10^{13}$ g, a factor of 5–15 less than inferred by [*Lellouch et al.*, 1994] for the G impact. In this model, the temperature of the plume is 274±10 K, taking into account the noise level, uncertainties on the flux calibration (20%) and on the dilution factor of the impact site in the aperture (+50%/-25%). This best fitting model is displayed in Fig. 2.

In the second class of models, we assumed that the CO column density was that given by Lellouch *et al.* (1.4×10^{18} molec cm^{-2}). Because the ^{12}CO emission originates higher than the ^{13}CO emission, a positive lapse rate (-dT/dlogp > 0 and assumed to be constant) allows us to reduce the intensities of the ^{13}CO lines with respect to the ^{12}CO lines. In this case, we derive a temperature difference of 37±8 K between the 10^{16} and 10^{18} CO molec cm^{-2} levels, i.e. over 4.5 CO density scale heights. The error bars correspond to the 1 SD noise uncertainty on the ^{13}CO lines. More conservatively, at the 3-σ level, we conclude that this temperature difference is at least 30 K. The temperature at the upper level is still 274±10 K, taking into account all uncertainties. If CO is uniformly mixed with gas above the 0.3–mbar level, the above atmospheric levels correspond to pressures of 2 and 200 μbar.

Since the present observations and those reported in Lellouch *et al.* refer to different impact sites (L and G) and different elapsed times since impact (4h30 and 10h), it is perhaps not surprising that the corresponding solutions are, at face value, different. Nevertheless, it is worth noting that a consistent solution for the two datasets can be found. Fitting the millimeter data with the thermal profile retrieved for our second class of models (T=274 K near 2μbar and T=237 K near 200μbar) leads to a column density of about 8×10^{27} molec cm^{-2}, i.e. 1.7 time less than in Lellouch *et al.*'s original analysis and in our modelling. This CO abundance and a profile warmer than given above by a few degrees would then satisfy both sets of observations. We defer a detailed joint analysis of millimeter and infrared observations to future work.

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Sushil K. Atreya, Department of Atmospheric, Oceanic and Space Sciences, Space Research Building, University of Michigan, Ann Arbor, Michigan 48109–2143, USA

Bruno Bézard, Catherine de Bergh, Pierre Drossart, Emmanuel Lellouch, André Marten, Département de Recherche Spatiale, CNRS-URA264, Observatoire de Paris, Section de Meudon, 92195 Meudon cedex, France

John Caldwell, Physics Department, York University, 4700 Keele Street, North York, Ontario M3J1P3, Canada

Jean-Claude Hilico, Laboratoire de Physique de l'Universite de Bourgogne, 6 Boulevard Gabriel, 21000 Dijon, France

Jean-Pierre Maillard, CNRS, Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France

(received December 7, 1994; revised February 2, 1995; accepted March 10, 1995.)