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The collision of comet Shoemaker-Levy 9 with Jupiter: Detection and Evolution of HCN in the stratosphere of the planet

A. Marten,[1] D. Gautier,[1] M.J. Griffin,[2] H.E. Matthews,[3] D.A. Naylor,[4]
G.R. Davis,[5] T. Owen,[6] G. Orton,[7] D. Bockelée-Morvan,[1] P. Colom,[1]
J. Crovisier,[1] E. Lellouch,[1] I. de Pater,[8] S. Atreya,[9] D. Strobel,[10]
B. Han,[6] and D.B. Sanders[6]

Abstract. We report submillimeter heterodyne observations of Jupiter taken with the JCMT during and after the infall of Comet Shoemaker–Levy 9 into the planet. We detected the J=4–3 and J=3–2 rotational transitions of HCN in emission at many of the impact sites. Measurements suggest for fragment G a mixing ratio of $\sim 5 \times 10^{-8}$ above the 0.5-mbar pressure level and a total HCN mass of 6×10^{11}g. Subsequent observations, made in September and November 1994, reveal that HCN is still present but that the lines now appear in absorption. This results from a cooling of the stratospheric thermal profile between July and September. Chemical implications of the observed persistence of HCN in the Jovian stratosphere for over 6 months are discussed.

Introduction

The high spectral resolution intrinsic to heterodyne techniques provides a powerful tool for searching for narrow stratospheric lines in planetary atmospheres. The observations of the Shoemaker–Levy 9 (SL9) impacts on Jupiter presented in this report are a part of a global strategy undertaken by a consortium of European, Canadian and US scientists. As a result of this strategy, searches for various molecules were made at the IRAM 30-m radiotelescope in Spain (Lellouch *et al.*, 1995, Marten *et al.*, 1994b), at the IRAM millimeter interferometer in France, (Wink *et al.*, 1994), at the SEST in Chile (Bockelée-Morvan *et al.*, 1994), and with the James Clerk Maxwell Telescope (JCMT) in Hawaii. This paper concerns the observations with the latter.

We report here the detections of the J=4–3 and J=3–2 transitions of HCN, at 354.51 and 265.89 GHz, respectively. These lines were observed in **emission** from July 16 to July 24, during and immediately following the cometary impacts. Subsequently, in September and November 1994, both lines were observed in **absorption.**

Observations

The JCMT double-sideband SIS mixer receivers (see Matthews, 1994) were used for this work. The observations concentrated on the J=4–3 transition of HCN; under poorer weather conditions we observed the J=3–2 line instead. An autocorrelation spectrometer was used to process the signals, with spectral resolutions of 756 kHz at 355 GHz and 189 kHz at 266 GHz. The total bandwidth sampled was 750 MHz for the HCN(4–3) observations and 250 MHz for those of HCN(3–2). At 355 GHz, the JCMT has a half-power beam width (HPBW) of 14 $''$ and a beam efficiency of 0.53; the corresponding numbers at 266 GHz are 21.5 $''$ and 0.70. The observations were carried out by modulating the secondary mirror position at 4 Hz, such that the receiver alternately viewed an impact site on Jupiter and a point 60$''$ distant in azimuth, well outside the disk of the planet.

Table 1 shows the impact sites tracked during the comet crash as well as detailed parameters corresponding to the observed lines. The line widths (in km/s) and integrated intensities (K km/s) result from Gaussian fits to the emission lines. Due to the relatively large beam width at both frequencies, several impact sites were usually present within the beam pattern at the end of the comet collision, making it difficult to discriminate which sites were dominating emission fluxes.

Results

We have selected the observations of HCN on the G impact site, performed on July 19. These observations,

[1] Observatoire de Paris–Meudon
[2] Queen Mary Westfield College, London
[3] Joint Astronomy Centre, Hilo, Hawaii
[4] University of Lethbridge, Canada
[5] University of Saskatchewan, Canada
[6] Institute for Astronomy, University of Hawaii
[7] Jet Propulsion Laboratory, California Institute of Technology
[8] University of California, Berkeley
[9] University of Michigan
[10] Johns Hopkins University, Baltimore

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Table 1. Detection of HCN emission features

Date U.T.	tracked[a] Impact	Impact date	time shift[b] d/h	I[c] K.km/s	Width km/s
		HCN	J(4–3)		
17.31	C	17.29	0/ 1	7.9	8.5
18.16	F	18.02	0/ 3	6.5	6.0
19.18	G	18.31	0/21	6.7	5.3
19.33	H	18.81	0/12	6.0	7.8
21.09	H		2/07	2.7	8.3
21.13	F		3/03	3.2	6.3
21.17	A	16.83	4/08	2.5	5.7
21.22	P2	20.64	0/14	6.0	12.3
21.27	R	21.23	0/01	8.5	8.0
		HCN	J(3–2)		
21.35	R		0/03	14.8	10.0
23.30	P2		2/16	2.0	7.3
23.35	R		2/03	6.1	5.5
25.10	R		3/21	8.1	14.7

[a] several fragments may contribute in the beam of the telescope after July 19.

[b] this column indicates the time delay (day/hour) between observations and impact times.

[c] integrated intensity in antenna temperature.

shown in Fig.1, are especially interesting since no other impact, except small impactor D, was present at this time in the beam of the radiotelescope. The interpretation of the observed spectrum requires the determination of the temperature structure and of the vertical distribution of HCN, which are a priori both unknown. However, the width of the line provides a strong constraint on the level of formation of HCN. The observed width ($\sim$ 5 km/s) is larger than any realistic Doppler broadening by several orders of magnitude, indicating the predominence of the collisional broadening process. In such a case, the observed value implies that HCN is not present in a detectable amount in the lower stratosphere. To model the emissions, we assumed a mixing ratio constant above a given pressure level. The location of this level was varied in calculations from the 0.5-mbar level up to 0.1-mbar level.

The contrast of the line with respect to the baseline provides a constraint on the temperature profile provided we are able to evaluate the correspondence between the antenna temperature and the brigthness temperature. This requires an estimate of the size of the HCN emitting region. We assume an emitting surface of 4 $\pm$ 0.5" in diameter, in agreement with the near infrared images of G, L and K impact sites recorded at IRTF by Orton *et al.* (1994). Compared to the HPBW at 355 GHz (14"), the 4" nominal size leads to a dilution factor of 34, which takes into account the beam efficiency and the coupling factor of the telescope. We adopted as a pre–impact nominal profile of Jupiter the model of Marten *et al.* (1994a) up to the 0.1-mbar pressure level, and the model of Atreya *et al.* (1981) above this level, which assumes 200 K at the 1 microbar level (Fig. 1).

It is clearly impossible to fit the measured spectrum from the nominal thermal profile of Jupiter, whatever the assumed HCN abundance. A good fit shown in Fig.1 results from a thermal profile that is warmer with respect to the nominal profile at all levels above the 1-mbar pressure level. The temperature excess is 40 K at the 0.2-mbar pressure level, and isothermal at the 210-K temperature above this level. The adopted vertical distribution of the mixing ratio (5 x 10^{-8} above the 0.5-mbar level) implies a HCN mass of $\sim$ 6 x 10^{11}g for fragment G. The solution for the temperature and the HCN abundance is obviously non–unique and higher concentrations of this species are possible. However, all solutions must satisfy simultaneously a linewidth of 5.3 km/s, and a temperature contrast of about 45 K. In other words, since the continuum is at $\sim$ 162 K, a temperature of $\sim$ 207 K at least must exist somewhere in the stratosphere.

Our observations permit us to follow the evolution of the HCN emission as a function of time. In Fig.2 are shown three spectra of the HCN (3–2) line recorded on July 21, 23 and 25 at the R fragment impact location. The interpretation of these results is less straightforward than that of Fig. 1, since several other impact sites were present in the beam of the radiotelescope, in particular G, Q1, Q2. The spectrum shown on the top of Fig. 2 (July 21) clearly exhibits a double peak which corresponds to the contribution from at least two different sites, presumably R and G: since sites rotate with the planet, their geocentric velocities and, accordingly, their Doppler shifts are different. The velocity difference depends both upon the respective site locations and observational time. The different shapes observed on July 23 and 25 mostly reflect changes in the relative emissions of contributing impact zones.

Between July 21 and 25 the peak intensity declined by about a factor of 2. We believe that this evolution results from a cooling of the temperature profile rather than a decrease of the HCN abundance. We are reinforced in this opinion by the appearance of HCN lines in absorption observed in September and November 1994 on various impact sites; strong lines were measured on Sept. 14 (site F), Nov. 9 (sites K, C), Nov. 18 (site F), Nov. 19 (sites K, G) and Nov. 21 (site C). Absorption and emission lines exhibit similar intensities. The level of the continuum should not have been modified during this time, since it originates from the troposphere. The contrast of the observed absorption lines implies that the stratospheric thermal profile was substantially cooler in September–November, may be by as much as several tens of degrees, than the pre–impact profile. As an example, Fig. 3b and 3c show the spectra of HCN (4–3) recorded on November 9 towards impact sites K and C. The observations centered on the Equator of Jupiter, Fig. 3a, indicate that the latitudinal size of the emission surface has not yet significantly increased at this date. The area of the absorption line suggests that the abundance of HCN has not substantially decreased since July. The modeling of the spectrum when several sites are present in the telescope beam is complex and requires additional work.

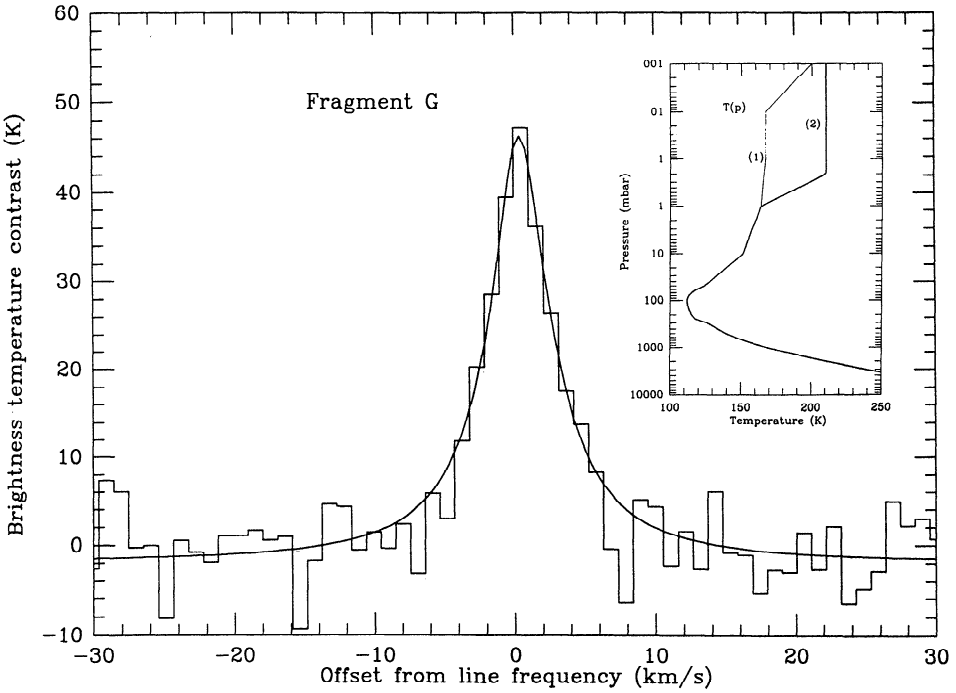

Figure 1. Observation of Jupiter in the HCN(4–3) line obtained on July 19, 1994 at the site location G. An emitting size of 4 arc sec was assumed to convert the measured antenna temperature into brightness temperature contrast. The spectral resolution is 1.5 MHz, corresponding to a velocity of 1.27 km/s. The inset shows the nominal profile of Jupiter (1) and the warm profile (2) used for the calculations. A synthetic spectrum calculated from the profile 2 and assuming a HCN mixing ratio of 5 x 10^{-8} above the 0.5 mbar pressure level is superimposed (full line).

Discussion

The present submillimeter observations clearly indicate that a strong warming occurred in the stratosphere after the impacts and persisted there at least up to July 24. This is consistent with the conclusions of Lellouch *et al.* (1995) derived from millimeter observations of CO, CS, and OCS. The infrared measurements of the CH_4 emission at 7.85 microns made by Orton *et al.* (1994) exhibit a less pronounced warming, of only a few kelvins. However, the observed infrared emissions originate from atmospheric levels located in the lower stratosphere, somewhat below the levels probed by millimeter measurements.

More enigmatic is the late cooling of the upper stratosphere down to temperatures substantially lower than their pre-impact values. This cooling trend, which still persists through late November 1994, was already present on July 28 according to millimeter observations of CO and CS made at IRAM (Lellouch *et al.*, 1995). Subsequent IRAM observations of CO during summer and fall confirm this behavior (Marten *et al.*, 1994b) although the intensities of the CO and, to a less extent, the CS line decline with time. The fact that the HCN line appears to vary much less suggests that it is very stable with respect to photochemical processes or its continued formation, as discussed below. Lellouch *et al.* (1995) attribute the unusual observed cooling to the sudden injection in the stratosphere of efficient infrared radiators such as HCN, NH_3 and may be H_2O if present in sufficient quantities. A substantial cooling could have been produced by the stratospheric particles generated by the SL9 impacts, a well-known process recognized a long time ago by Benjamin Franklin (1784). Such aerosols, which reflect sunlight, have been observed in the near-infrared (Rosenqvist *et al.*, 1994, Orton *et al.*, 1994). Since they are located at altitudes below the 1 mbar level, the resulting cooling is more effective in the lower stratosphere.

There are two possible sources of the observed HCN: photochemistry and high temperature shock-thermo-

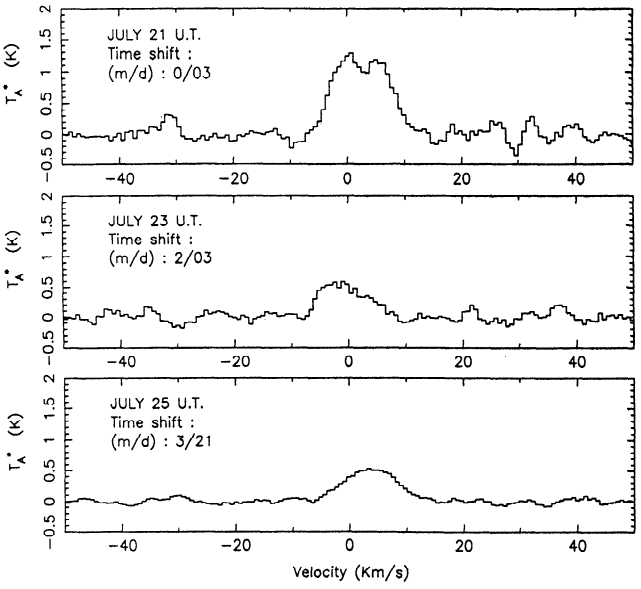

Figure 2. Antenna temperature spectra of the HCN (3–2) line centered at 265.89 GHz, recorded on July 21, 23 and 25. In each case, the telescope was tracking the site R. The spectral resolution is 0.76 MHz. The velocity scale refers to impact R.

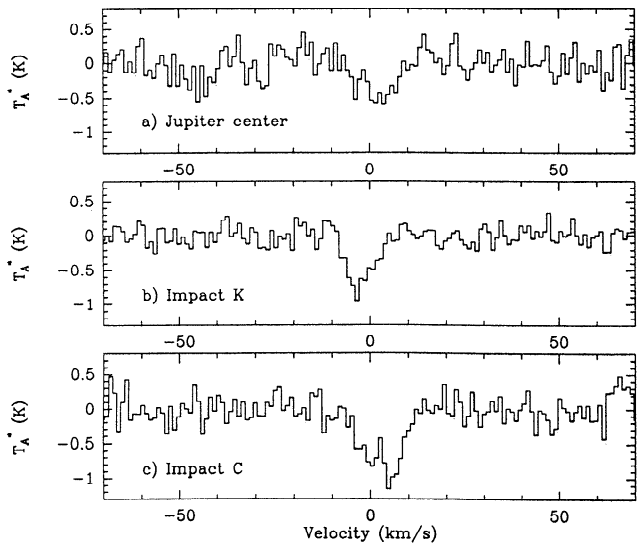

Figure 3. HCN (4–3) lines observed on November 9, 1994, between 19:50 and 20:25 U.T. The spectral resolution is 1.5 MHz. The velocity scale is geocentric. The beam was pointed on the center of Jupiter (a), on impact sites K (b) and C (c). Due to the small angular separation between impact sites K and C ($\sim$ 9"), and between the impact sites and the center of Jupiter (8 – 10"), compared to the HPBW of 14", the three spectra reflect HCN absorption on both impact sites K and C.

chemistry. In principle, HCN could have been produced photochemically but this is unlikely: photochemical production of HCN is solar photon limited and there was not enough time to enhance the HCN mixing ratio by a significant factor. The second scenario implies that this species was formed in the region of explosion, through shock-induced chemistry. The explosion must have occured where large quantities of CH_4 and NH_3 gases are available, i.e. below the NH_3-ice cloud located at $\sim$ 0.6-bar pressure level. This is consistent with the large increase of the stratospheric ammonia abundance observed by Orton *et al.* (1994), Atreya *et al.* (1994) and Noll *et al.* (1994).

Once formed, HCN is photochemically stable in the Jovian atmosphere. Although the optically thin dissociation lifetime is approximatively 1.2 x 10^6 s, absorption of solar radiation by CH_4, C_2H_2, and C_2H_6 above the 0.1 mb level increases this lifetime to $\sim$ 3 x 10^8 s. The dissociation-generated CN radical will react subsequently with one of the above hydrocarbons, but only its reaction with C_2H_2 yields a product (HC_3N) other than HCN initially. The probability of initially NOT reforming HCN is about 0.004, thus effectively increasing the lifetime of HCN at 0.1 mb level to about 7 x 10^{10} s. Photolysis of HC_3N yields CN, which may react with hydrocarbons to recycle HCN and lower the above probability even further. Although a detailed photochemical model would be needed to obtain precise values, it is clear that the governing time constant for HCN is the vertical mixing time ($\geq$ 3 yr, Allen *et al.*, 1992).

We conclude that, barring any major dilution due to planetwide transport, HCN should persist in the Jupiter's stratosphere at detectable amounts for months or years. The most recent measurements made at JCMT in January 1995 confirm it is still present. Observations at this radiotelescope will be pursued.

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A. Marten, Observatoire de Paris-Meudon, F-92195 Meudon, France

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