Search for NH$_3$ in Jupiter’s Stratosphere Ten Months after SL9’s Collision

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The collisions also injected tropospheric ammonia (NH$_3$) in the stratosphere where it is ordinarily absent. Signatures from stratospheric ammonia were detected from thermal infrared spectroscopy at the NASA Infrared Telescope Facility (IRTF) (Orton et al. 1995) and from ultraviolet observations made with the Hubble Space Telescope’s (HST) Faint Object Spectrograph (FOS) (Noll et al. 1995). High-resolution observations of two ammonia lines at 908 and 948 cm$^{-1}$ were performed over the K site at the IRTF on July 20, 25, 30, and 31, 1994 UT using the Irshell spectrometer. A detailed analysis of these spectra indicates that the bulk of the NH$_3$ resided in the lower stratosphere around the 20-mbar level (Griffith et al. 1996). A comprehensive investigation of the HST/FOS spectral observations of the G site in July and August 1994 shows that most of the NH$_3$ was mixed with the impact debris and lay below CS$_2$, a species formed by shock chemistry and deposited in the reentry shock region (Yelle and McGrath 1996). The vertical placement of NH$_3$ as determined by the Irshell observations coincides with the atmospheric region of maximum static stability where stratospheric waves may have deposited large quantities of tropospheric jovian air (Young et al. 1995). In addition, Irshell observations on July 20 UT give evidence for a separate, less abundant source of NH$_3$ at higher levels (Griffith et al. 1996). This is supported by heterodyne observations of the 892–cm$^{-1}$ NH$_3$ line over the Q1 and RSG complex showing that some NH$_3$ was present above 10 mbar (Kostiuk et al. 1996). This smaller amount of NH$_3$ probably originates from quenching of the fireball as it rose through the atmosphere.

1. INTRODUCTION

The impacts of the fragments from Comet D/Shoemaker–Levy 9 locally modified the composition of Jupiter’s stratosphere. Most of the new molecular species (CO, HCN, C$_2$H$_6$, C$_2$, OCS) were formed by shock chemistry during the explosions and during the fallback of the ejecta plumes in the atmosphere. They were deposited in the upper stratosphere, above the $\sim$0.1-mbar region, where the reentry shocks occurred (Zahnle and Mac Low 1995).

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and cooled (Zahnle 1996). The observed NH₃ survived the reentry shock and was deposited with the plume above ∼0.1 mbar. Ammonia is efficiently photolyzed by ultraviolet radiation in the region 170–220 nm. Photochemical calculations indicate a photolysis lifetime in the upper atmosphere of approximately 5 days (Moses et al. 1995b). However, Irshell observations show that the NH₃ column density was the same within errors over the K site on July 20 and July 30, 1994 (Griffith et al. 1996). Ultraviolet HST/FOS observations consistently show that the ammonia mixing ratio on the G site did not vary between July 18 and August 9, but was depleted by a factor of 3 on August 23 (Yelle and McGrath 1996). This persistence suggests that self-shielding and shielding by other molecules and debris particles efficiently protected ammonia from photolysis on a time scale longer than the optically thin lifetime. A more recent photochemical model presented by Moses et al. (1995a) suggests that shielding could be so efficient that NH₃ is depleted only by a factor of 7, 500 days after impact. Ammonia would then remain detectable in Jupiter's stratosphere longer than a year. In fact, McGrath et al. (1995a, b) reported the detection of stratospheric ammonia around the latitude of impacts (45° S) from HST/FOS observations in March and April 1995, 9 to 10 months after the collision.

Here, we report high-resolution observations of the impact belt conducted in May 1995 with the Irshell instrument mounted at the IRTF. Our goal was to search for a possible persistence of the compounds (HCN, CH₃NH₂, NH₃) detected with the same instrument in July 1994 (Beetzard et al. 1996; Griffith et al. 1996). Temperature perturbations were also investigated by mapping the intensity of CH₄, C₂H₂, and C₂H₆ lines in the southern hemisphere (Bećzard et al. 1995a). No thermal anomaly exceeding the instrument sensitivity was detected around the impact latitude. This paper presents the NH₃ spectral observations and their analysis to investigate the survival of ammonia in the jovian stratosphere. Observations of HCN will be presented in a forthcoming paper.

2. OBSERVATIONS

Observations were made with the Irshell spectrometer (Lacy et al. 1989) mounted at the NASA/IRTF on the nights of 1995 May 15–18 UT. The detector was a 11 spatial × 64 spectral element array used in previous runs (Bećzard et al. 1995b). The 11–arcsec long slit was oriented along the east–west planetocentric direction allowing for simultaneous observations of 11 different positions separated by 1.0 arcsec. Spectral maps between approximately 25 and 55° S of latitude were obtained by stepping the telescope in Jupiter’s north–south direction with steps of 1 arcsec. The slit width was set to 1.5 arcsec which should have yielded a resolving power of ∼16,000. However, because the detector plane was slightly out of focus, the actual spatial resolution was ∼2.5 arcsec and the resolving power was around 10,000 (as determined from observations of CH₄ and C₂H₂ unresolved lines).

The NH₃ observations presented here were recorded on May 16 1995 UT. The grating covered the 907.5– to 910-cm⁻¹ interval that includes the strong ammonia multiplet sP(3,K) of the ν₁ band. This multiplet consists of three lines at 908.11, 908.18, and 908.20 cm⁻¹ that cannot be distinguished at our spectral resolution (0.09 cm⁻¹). Observations implemented the “nod” observing mode (Lacy et al. 1989), with the telescope adjusted to nod every few seconds with an amplitude of 40 arcsec. Eight to 10 slit positions on the disk separated by 1 arcsec were recorded with an on-source integration time of 40 sec per position. The S/N ratio was ∼70 in the wings of the NH₃ line, and ∼40 in the absorption core. We applied the procedures for flat fielding, correction of atmospheric absorption, and intensity calibration described in Lacy et al. (1989) and Bećzard et al. (1995b). The uncertainty on the absolute intensity calibration is ∼10%.

3. RESULTS

a. Maps of the NH₃ Line

Figure 1 shows a typical spectrum recorded at 45° S in which absorption from tropospheric ammonia is clearly visible. Ten months after SL9 impacts, no emission is detected in the core of the NH₃ line, in contrast to observations of the same line on July 20 and 25, 1994 (Griffith et al. 1996). In fact, stratospheric emission was not present in any of the Irshell spectra recorded in May 1995. This absence indicates that the ammonia left in the stratosphere 10 months after the collision had dropped below our instrument sensitivity.

Maps of the radiation in the wing (909.4–909.8 cm⁻¹) and in the core of the NH₃ line at 908.2 cm⁻¹ are presented in Fig. 2. The radiation at the line center derives from a least–squares quadratic fit of the data points between 908.0 and 908.4 cm⁻¹. The NH₃ wing map shows the expected limb–darkening behavior, with no particular feature around the impact belt. The NH₃ core probes the upper troposphere near 250 mbar, a region of weaker lapse rate and stronger gradient in the NH₃ profile. The radiation at 908.2 cm⁻¹ is consequently less sensitive to the jovian air-mass than that in the line wings probing the ∼450-mbar region. Limb-darkening is much less pronounced and the latitudinal structure in the 908.2-cm⁻¹ map reflects real variations in the line forming region. A brighter region is seen around the latitude of the impacts, roughly between 35° and 55° S. The coldest region is found around 25° S. As mentioned above, inspection of individual spectra clearly indicates that the higher radiances found at the line core around 45° S do not reveal the presence of strato-
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FIG. 1. Inshell spectra of the 908-cm⁻¹ NH₃ line recorded on July 20 and 25, 1994 UT and on May 16, 1995 UT. The July 1994 spectra were recorded at the location of the K impact with a resolution of 0.06 cm⁻¹. They have been corrected for the Doppler shift due to the Jupiter–Earth motion and the rotation of the planet. The May 1996 spectrum was recorded at the latitude of the impacts with a resolution of 0.09 cm⁻¹. The 1 SD noise level is 0.0045 erg sec⁻¹ cm⁻² sr⁻¹. None of the spectra recorded in May 1996 exhibits an emission core exceeding noise.

spheric emission. They could result either from a depletion in the NH₃ abundance or from larger temperatures near 250 mbar.

Ammonia depletion is not expected to result from the impacts. Upwelling motions which occurred shortly after the explosions caused local enhancements of the NH₃ concentration in the stratosphere and possibly in the upper troposphere (Griffith et al. 1996). Also, in the quiescent Jupiter, the NH₃ mole fraction was found to be constant within uncertainties in the 25° to 60° S range at the Voyager encounter (Gierasch et al. 1986). On the other hand, temperature contrasts are known to be present in Jupiter’s upper troposphere (e.g., Gierasch et al. 1986). It is thus natural to first try to interpret the observed variations in the NH₃ line by variations in the thermal structure of the troposphere.

b. Radiative Transfer Calculations

Synthetic spectra were generated from the line-by-line radiative transfer program described in the analysis of our July 1994 observations (Bezard et al. 1996, Griffith et al. 1996). Spectroscopic parameters are given in these two papers. We first considered spectra recorded at the impact latitude (45° S) to derive upper limits on the stratospheric NH₃ abundance. We used the nominal temperature profile derived by Bezard et al. (1996) from observations of CH₄ lines in July 1994 near 45° S, outside of the impact sites. The tropospheric ammonia profile from Fig. 3 of Griffith et al. (1996) allowed us to reproduce approximately the absorption line in the May 1995 data.

An emission core appears in the synthetic spectra when ammonia is added in the stratosphere above ~40 mbar. To derive a stringent upper limit on stratospheric ammonia, we compared calculations to an average of 24 spectra recorded around the latitude of the impacts (Fig. 3). These correspond to Columns 6–8 and Rows 4–11 in the maps of Fig. 2b. The 3 SD upper limit for detection of an emission feature in this selection is thus $3 \times \frac{0.0045}{2.5} \times 24 = 0.002$ erg sec⁻¹ cm⁻² sr⁻¹, where 2.5 stands for the number of pixels covered by the instrument function. This level amounts to about 1% of the radiance observed in the absorption core of the NH₃ line. However, our sensitivity may be limited by the accuracy with which atmospheric absorption is removed and flat fielding is achieved. Consid-
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FIG. 3. An average of 24 spectra recorded around 45° S is compared with three synthetic spectra. The nominal one was generated with no stratospheric ammonia and shows no emission at the line center. The two other spectra, showing increasingly stronger emission cores, include respectively 0.5 and 1 × 10¹⁶ molecule cm⁻² uniformly distributed above 40 mbar. The slight depression in the observed spectrum around 908.9 cm⁻¹ is due to imperfect correction of an H₂O telluric line.

Considering the quality of our data, we would have reliably detected any feature larger than 2% of the radiance in the NH₃ absorption line, based on previous experience (e.g., Bézard et al. 1995b). This 2% criterion is conservative considering the excellent transmission of the Earth’s atmosphere between 907 and 908.6 cm⁻¹ (higher than 99%).

We first included NH₃ with a mixing ratio constant above the 40-mbar level, and derived the value yielding a 2% emission feature at the line core. The maximum NH₃ mixing ratio is 0.8 × 10⁻⁴, corresponding to a column density of 4 × 10¹⁵ molecule cm⁻². We also tried constant mixing ratio distributions having higher cutoff levels in the stratosphere. They yield lower values for the maximum column density because ammonia is then located at warmer levels and contributes more efficiently to the thermal emission.

Finally, we considered a NH₃ distribution confined in the region 15–35 mbar. This is the region where the bulk of the stratospheric ammonia was injected by the K impactor (Griffith et al. 1996). For this distribution, we derived a maximum column density of 6 × 10¹⁵ molecule cm⁻².

Ammonia can “hide” in the stratosphere and not be detected with Irshell only if it lies around 60 mbar. At this pressure level, the ambient temperature (120 K) is similar to that at 250 mbar where the NH₃ absorption core is formed; i.e., the temperature contrast is null. We regard this possibility as very unlikely because ammonia was originally deposited around 20–25 mbar. As discussed by Griffith et al., this is the region of maximum static stability so that mixing is probably very sluggish. Eddy mixing profiles constrained by the results of Conrath and Gierasch (1984)

FIG. 2. Irshell spectral images produced from two scans (left and right, respectively). Horizontal and vertical scales represent the pixel position in arcsec in the East and South directions respectively. Position (1,1) is that of the first pixel of the array for the first integration step. Panels show respectively, from top to bottom, the intensity in the wing of the NH₃ line (909.6 cm⁻¹), the intensity at the center of the line (908.2 cm⁻¹), and a sketch showing the location of the visible impact sites. In this sketch, the horizontal and vertical axes represent the angular distance (arcsec) from the center of the jovian disk as seen from the Earth, in the jovian north and east directions respectively.
FIG. 4. Temperature and ammonia profiles used to generate the synthetic spectra in Fig. 5. Tropospheric temperatures in the "cold" profile were derived from a selection of Voyager infrared spectra recorded near 25° S (Griffith et al. 1992). This profile was perturbed around the tropopause to produce a "warm" profile allowing us to fit the spectra around 45° S.

yield a diffusion time of about 15 years in the 20-mbar region (Gladstone et al. 1996, Allen et al. 1992). Similarly, investigations of the thermal structure of Jupiter from Voyager infrared data (Comrath et al. 1981) indicate an upper limit of ~20 years for the mixing time at the tropopause. We conclude that, if ammonia survived, it should still be in the same region 10 months after SL9 collision. We also note that species such as CO or CS, generated from shock chemistry, are still detected in the same region as they were deposited a year before (0.1–0.3 mbar) (Moreno et al. 1995).

We also investigated the latitudinal variations in the NH₃ absorption line. We started modeling the spectra recorded at 27° S, i.e., corresponding to the first column in the radiance maps (Fig. 2). We used the nominal temperature profile from Bezard et al. (1996) in which the tropospheric part was retrieved from Voyager infrared spectra of the StrZ around 25° S of latitude (Griffith et al. 1992). This profile, denoted as "cold," is displayed in Fig. 4. An ammonia profile, shown in the same figure, was then retrieved from the observed line profile.

Figure 5 presents a set of 10 spectra extracted from the scan of Fig. 2b and recorded at the same longitude (210° W). Dashed lines represent synthetic spectra calculated for each location using the above atmospheric model. While the spectrum observed at 27° S is well reproduced by the model, the latter yields too low radiances at more southern latitudes. We have then produced a warmer temperature profile ("warm" in Fig. 4) by warming up the nominal one around the tropopause. The series of spectra generated with this temperature model and the same NH₃ profile as before are shown as solid lines in Fig. 5. They provide a good reproduction of the spectra at latitudes in the range 35° to 50° S. Variations of the thermal structure in the upper troposphere are thus capable of explaining the observed variations in the NH₃ absorption line. The required temperature variations agree with previous studies of the tropospheric temperature field, as discussed in the next section.

4. DISCUSSION

We derived an upper limit of 6 × 10²⁵ molecule cm⁻² for the column density of stratospheric ammonia above 40 mbar at the impact latitude 10 months after the collision. From infrared heterodyne spectroscopy, Kostiuk et al. (1995) reported an upper limit of a few 10⁻³⁰ for the NH₃ mixing ratio 8 months after impact. However, due to S/N...
FIG. 5. Irshell spectra recorded on May 16, 1995 (13:16 UT) at longitude 210° W are compared to two series of synthetic spectra calculated with the "cold" and "warm" temperature profiles of Fig. 4. Spectra are shifted by 0.15 cm⁻¹ sr⁻¹ from one latitude to another. The "warm" temperature profile yields a good reproduction of the NH₃ spectra in the latitude range 35° ± 55° S, while the "cold" profile allows us to fit the 27° S spectrum.

limitations, their data are almost insensitive to pressure levels larger than 20 mbar, the region where most of the stratospheric ammonia resided following the impacts. Their results complement ours; they point to the lack of high-altitude NH₃ (less than a few 10¹⁴ molecule cm⁻² above 10 mbar).

McGrath et al. (1995a, b) presented HST/FOS observations in the impact regions showing NH₃ absorption 8 to 9 months after the collision. No quantitative estimation of the NH₃ abundance was given. It is possible that these UV observations are more sensitive than Irshell observations. The maximum absorption cross section of NH₃ is about 2 × 10⁻¹⁵ cm² near 1900±2000 Å (Atreya 1986). Our upper limit would then yield a vertical optical depth of 0.1 that may be detectable by UV observations if the aerosol extinction in the stratosphere is low enough. On the other hand, we note that McGrath et al. only presented ratios of post-to-pre-impact spectra recorded at the impact latitude. In the unperturbed Jupiter, absorption from tropospheric ammonia was detected in UV spectra recorded at relatively low solar incidence and emission angles (Wagener et al. 1985, 1986), but not for large values of these angles (e.g., Fig. 5 of Yelle and McGrath 1996). We think it is still unclear whether ratios of pre- to post-impact spectra might show NH₃ absorption features resulting from long-term variations in the NH₃ tropospheric profile or in the aerosol scattering properties, rather than from the presence of some stratospheric ammonia. Any reliable conclusion on this question awaits a full analysis of the HST/FOS spectra.

Horizontal eddy mixing acts to dilute the NH₃ column density present over the impact sites. High-resolution UV images from the HST indicate that the stratospheric dust particles generated by the impacts had spread to about 20° S in March and September 1995 (West 1996), thus covering an area ≈ 2 × 10¹⁰ km². The K impact injected about 3 × 10¹⁵ g of NH₃ in the lower stratosphere (Griffith et al. 1996). It also generated ~2 × 10¹⁵ g of HCN, representing about 1/5 of the total mass created by all fragments (Bézard et al. 1996). Applying the same scaling factor of 5 to the mass of NH₃, we estimate that ~1.5 × 10¹⁴ g of ammonia were upwelled in the jovian stratosphere by all the SL9 fragments. Assuming that this compound spread...
over 10 months similarly to the dust particles, its column density would amount to \(3 \times 10^{17}\) molecule cm\(^{-2}\), i.e., about seven times less than measured over the K site in July 1994 (Griffith et al. 1996). This is still five times larger than the upper limit we derived from our May 1995 observations, indicating that horizontal diffusion alone cannot account for the nondetection of ammonia.

As discussed by Moses (1996), our nondetection of stratospheric ammonia 10 months after the impacts is expected from photochemical models with no dust shielding (Moses et al. 1995b). Assuming that \(1.5 \times 10^{17}\) molecule cm\(^{-2}\) of NH\(_3\) were initially deposited by the impacts above 1 mbar, Moses et al.’s model predicts that only \(10^{16}\) molecule cm\(^{-2}\) are left after 10 months, which is consistent with our observations. More recently, Moses et al. (1995a) investigated the effect of dust on the photochemistry, using constraints from West et al. (1995) and assuming a given time variation in the haze opacity. This model predicts that about \(10^{17}\) molecule cm\(^{-2}\) would have survived 10 months, in contradiction with our upper limit. However, their model did not account for horizontal spreading. If this mechanism alone decreases the column density by a factor of 7, as we estimated above, the predicted NH\(_3\) column density would be on the order of \(1.5 \times 10^{17}\) molecule cm\(^{-2}\), still twice larger than our upper limit. Therefore, it seems that too much shielding was introduced in their model, although a firm conclusion would require more sophisticated photochemical calculations incorporating horizontal dilution.

Our observations suggest that most of the ammonia had been photochemically removed in May 1995, and hence that the dust is not optically thick in the UV around 20–30 mbar during the first 2–3 months of the impacts. It was not the case in July 1994. A comparison of NH\(_3\) line observations with Irshell and HST/FOS (Yelle and McGrath 1996) indicates that the aerosol optical depth reached unity within the dust layer and 150-mbar regions, respectively. The IRTF images show a pattern similar to the Voyager results, with warmer regions located around the NEB, the SEB, southward of 40° S, and northward of 30° N (Fig. 5 of Orton et al.). Cooler regions were the EqZ, the STrZ, and to a lesser extent the NTrZ. Contrasts were less visible in the 13.0-µm images which probe deeper in the troposphere. The thermal structure indicated by these images agrees well with the May 1995 Irshell measurements. We conclude that the horizontal variations we detected in the NH\(_3\) line are very likely result from the normal structure of the tropospheric temperature field, linked to the general atmospheric circulation. There is no evidence for an abnormal NH\(_3\) distribution at the impact latitude.

In conclusion, the ammonia distribution in the stratosphere and upper troposphere was back to normal 10 months after the impacts, within the sensitivity of our observations. This behavior contrasts that of other species formed by shock-chemistry and deposited in the upper stratosphere. These compounds (HCN, CO, CS), harder against ultraviolet radiation, still give evidence today of the large perturbations caused by the SL9 collision.

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**References**


structure of the jovian stratosphere. Icarus 121, 236–256.


HERNBERG, R., AND J. CALDWELL 1984. The Jovian

HERNBERG, R., AND J. CALDWELL 1984. The Jovian

HERNBERG, R., AND J. CALDWELL 1984. The Jovian

HERNBERG, R., AND J. CALDWELL 1984. The Jovian

HENNING, M., AND J. CALDWELL 1984. The Jovian

HENNING, M., AND J. CALDWELL 1984. The Jovian

HENNING, M., AND J. CALDWELL 1984. The Jovian

HENNING, M., AND J. CALDWELL 1984. The Jovian

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