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Upper Limits on Spacecraft-Induced Ultraviolet Emissions From the Space Shuttle (STS-61C)

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Ultraviolet spacecraft-induced emissions from low Earth-orbiting satellites have been reported by several investigators. Several R/Å of ultraviolet emission were observed from the S3-4 satellite at altitudes between 180 and 250 km and from the Spacelab 1 shuttle mission at an altitude of 250 km. Conway et al. (1987) showed that N_2 Lyman-Birge-Hopfield (LBH) emissions observed by S3-4 at night are probably the result of spacecraft interaction with the atmosphere. We have searched for band emission of N_2, OH, O_2, and NO in nightglow spectra obtained in January 1986 with the Johns Hopkins ultraviolet background experiment (UVX) flown on the space shuttle *Columbia* (STS-61C) at an altitude of 330 km. The experiment consisted of two Ebert monochromators spanning the spectral range from 1200 to 1700 Å at 17 Å resolution and from 1600 to 3200 Å at 29 Å resolution. The spectra yield 3σ upper limits for the following total band emission rates: NO δ, 0.6 R; NO γ, 0.7 R; NO β, 3.5 R; O_2 Herzberg I, 4.5 R; OH $(A^2\Sigma_u^+ - X^2\Pi)(0,0)$ and (1,0), 0.1 R, and N_2 LBH, 5.3 R. The upper limits for the N_2 LBH emissions are consistent with the recent models of spacecraft induced LBH glow of Kofsky (1988), Swenson and Meyerott (1988), and Cuthbertson and Langer (1989) and with a $[N_2]^3$ or $[N_2]^2[O]$ altitude dependence.

1. INTRODUCTION

Spacecraft glows originating from the interaction between the atmosphere and low Earth-orbiting spacecraft have been reported by several investigators. Near-ultraviolet to infrared glows were first observed from the Atmosphere Explorer C satellite [*Torr et al.*, 1977; *Yee and Abreu*, 1983] and later on the space shuttle beginning with the STS-3 spacecraft [*Banks et al.*, 1983]. More recently, spacecraft interactions with the atmosphere have been shown to be the source of the far ultraviolet N_2 Lyman-Birge-Hopfield (LBH) bands observed at night [*Huffman et al.*, 1980; *Conway et al.*, 1987] from the S3-4 satellite. Conway et al. also demonstrated that the emission depended strongly on the altitude of the satellite, with either a $[N_2]^3$ or $[N_2]^2[O]$ dependence between 180 and 250 km. Similar emission, also at a level of several R/Å, has also been observed in spectra from the space shuttle Spacelab 1 experiment [*Torr et al.*, 1985] from an altitude of 250 km. Various mechanisms have been proposed to explain the induced N_2 LBH glow [*Kofsky*, 1988; *Swenson and Meyerott*, 1988; *Cuthbertson and Langer*, 1989] that are consistent with a $[N_2]^3$ or $[N_2]^2[O]$ altitude dependence.

We have searched for N_2 LBH emission in the nightglow spectra obtained between January 13 and 15, 1986, with the Johns Hopkins (JHU) ultraviolet background experiment (UVX) flown on the space shuttle *Columbia* (STS-61C) at an altitude of 330 km. Very few spacecraft have had instruments which have been able to address the question of shuttle glow in the ultraviolet. Good spectral resolution as well as high sensitivity are needed. Most experiments designed for airglow observations have been primarily nadir viewing and have not been able to make observations in the spacecraft ram and wake with the exception of the Spacelab 1 experiment [*Torr et al.*, 1985].

UVX was designed primarily to make observations of the diffuse cosmic background in the ultraviolet [*Murthy et al.*, 1989, 1990]. Since the UVX experiment was observing astronomical targets, it was pointed inertially, and consequently, there were instances where it observed into the ram, perpendicular to it, and into the wake. UVX had moderate spectral resolution (17 Å or 29 Å), high sensitivity (~0.003 R/Å), and a wide field of view (4° × 0.26°).

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2. INSTRUMENTATION

The JHU UVX experiment was an advanced Get-Away-Special (GAS) payload that flew on the space shuttle *Columbia* (STS-61C) launched on January 12, 1986. UVX was a self-contained experiment including its own power, data storage, and experiment control. The experiment consisted of two 0.25-m Ebert-Fastie scanning monochromators placed at the respective foci of two 39-cm focal length off-axis paraboloid telescope mirrors. The two monochromators covered the spectral range from 1200 to 1700 Å at 17 Å resolution (G-tube) and from 1600 to 3200 Å at 29 Å resolution (F-tube) at 10 s per scan. The fields of view of both instruments were 4° by 0.26°. Neither instrument viewed any shuttle surfaces, although an entrance aperture plate at the end of the GAS can was visible. The instruments were calibrated both preflight and postflight using the Calibration Test Equipment at JHU [*Fastie and Kerr*, 1975], and the absolute sensitivity was found to be reproducible to within ±15%. The uncertainty in the absolute calibration of the entire system is ±20%. Both monochromators and their associated optics were mounted inside a GAS can equipped with a motorized door assembly. The avionics were contained in another nonopening GAS can. The GAS cans were sealed until orbit at which point the doors were opened and left open for 24 hours to allow complete outgassing of the payloads. The shuttle was placed in a 330-km circular orbit at 28° inclination. The UVX experiment observed nine celestial targets with an exposure time of ~30 min per target during the night portions of the orbit. Spectra obtained from the shorter wavelength G-tube detector suffered from a high

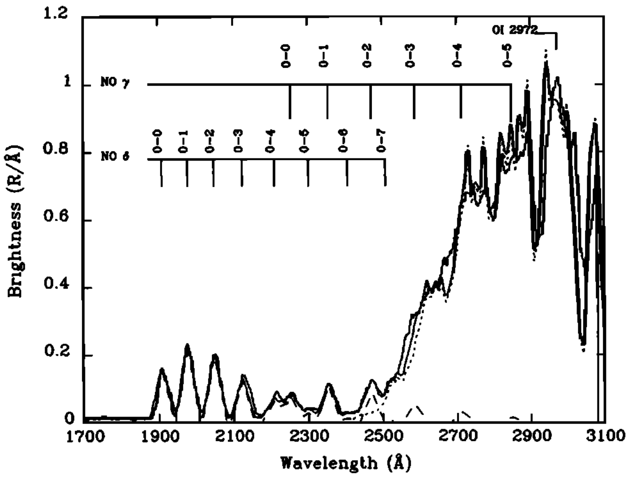

Fig. 1. Limb viewing spectrum of target 9. Also shown are synthetic spectra of the NO δ and γ bands and the O_2 Herzberg bands. The NO δ and γ band ratios are taken from *Barth* [1965] and *Piper and Cowles* [1986], respectively, and the O_2 Herzberg band intensities are taken from *Degen* [1977].

dark rate that varied considerably from orbit to orbit. Observational details are given by *Murthy et al.* [1989, 1990].

The primary objective of the UVX instrument was the study of diffuse cosmic background radiation including the measurement of the ultraviolet properties of the zodiacal light. The instruments' large field of view and high sensitivity (~0.1 R for line emissions) provided an excellent means of studying spacecraft induced emissions and had as a secondary goal the determination of any possible adverse influence of the shuttle orbiter on ultraviolet astronomy.

3. OBSERVATIONS

Previously, *Tennyson et al.* [1987] made a preliminary spectral search for spacecraft induced atomic oxygen line emissions and NO, OH, and O_2 molecular emissions observed with the UVX experiment. No emissions were seen that were inconsistent with terrestrial sources although a detailed comparison between ram and wake observations was not made. A search for nocturnal N_2 LBH emission was not made. We have subsequently analyzed spectra from the short wavelength monochromator to look for N_2 LBH emission and from the long-wavelength monochromator to look in greater detail for NO δ, γ, and β bands, O_2 Herzberg band emission, and OH ($A^2\Sigma_u^+ - X^2\Pi$)(0,0) and (1,0) band emission at 3064 Å and 2811 Å, respectively.

UVX observed the celestial targets into either the morning or the evening limb on each orbit. As a consequence, NO δ and γ bands as well as O_2 Herzberg bands are readily seen when viewing the limb. Figure 1 shows a typical limb viewing spectrum. Also shown in Figure 1 are synthetic spectra of the NO δ, γ, and β bands, and the O_2 Herzberg bands. The NO δ and β band branching ratios are taken from *Barth* [1965] and the γ band ratios are taken from *Piper and Cowles* [1986]. The O_2 Herzberg band intensities are taken from *Degen* [1977]. The branching ratio of the NO $C^2\Pi$ state to the $A^2\Sigma^+$ state is determined from the ratio of the total emission rate from the δ band system to that of the γ band system. From the limb viewing data we can determine the best fit for the δ to γ band ratio and thus determine the $C^2\Pi$ to the $A^2\Sigma^+$ branching ratio. Using the fits from the synthetic spectra, the derived branching ratio for the $C^2\Pi$ state to the $A^2\Sigma^+$ state is 0.37 ± 0.03. This is greater than the value of 0.30 ± 0.06 derived by *Tennyson et al.* [1986] from sounding rocket data and much larger than the values of 0.23 and 0.21 ± 0.04 derived from independent sounding rocket measurements by *McCoy* [1983] and *Sharp and Rusch* [1981], respectively. It is close to the laboratory value of 0.43 found by *Callear and Pilling* [1970]. As can be seen from Figure 1, with the exception of some of the O_2 Herzberg bands the match to the synthetic spectrum is quite good. The slit orientation, however, was determined by celestial targets and the requirement to avoid potential bright stellar sources, so that for none of the nine targets was the slit aligned parallel to the Earth's limb. Due to the long slit length (4°) and the long scan time (10 s per scan) it is not possible to determine altitude profiles for any of the observed emissions.

A map of the Earth with the nighttime observation periods indicated as curved lines along with the target numbers is shown in Figure 2. For our purposes, three subsets of the UVX observations were selected according to the viewing direction. In the first set, the instrument was pointed within 20° of the ram direction; in the second, the pointing was within 20° of the perpendicular to the ram; and in the third, the pointing was within 20° of the wake. Target portions falling in any of these three cases are shown by the solid parts of the orbital path on Figure 2. On only a very few of the targets were these conditions met. Observing near the ram occurred only for targets 3 and 9, while only on target 8 the shuttle wake was observed.

As an illustration, the results from target 9 are considered. On this target, UVX made a 12° scan of the sky and viewed into the shuttle ram and perpendicular to it. The short-wavelength G-tube monochromator had its lowest noise level on this target as well (3–6 counts s^{-1} compared to a maximum rate of 40–100 counts s^{-1} for target 3).

The spectrum obtained viewing into the ram is shown in

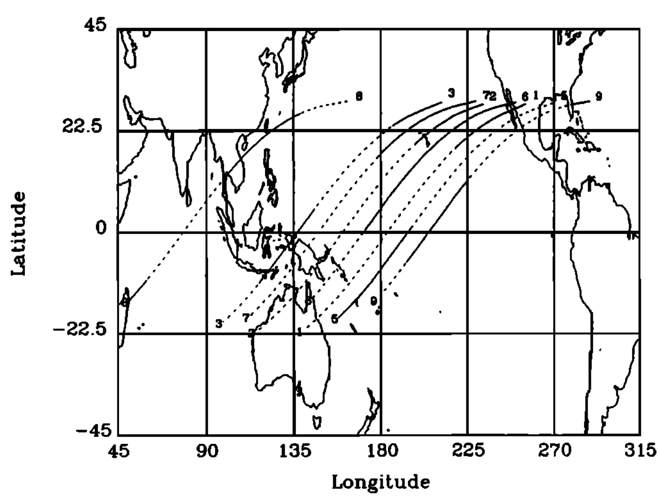

Fig. 2. A map of the Earth showing the portions of the orbit during which data were taken. The solid lines indicate when viewing either in the ram, the wake, or perpendicular to the ram direction. The lines are labeled with the target numbers from Table 2 of *Murthy et al.* [1989].

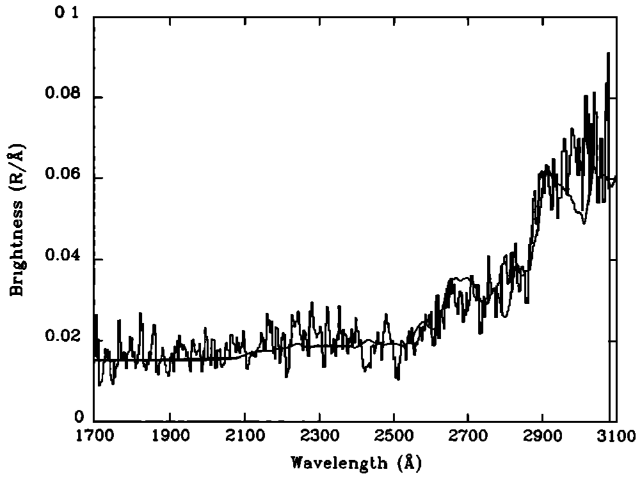

Fig. 3. The spectrum of target 9 when viewing into the velocity vector (ram). The long-wavelength emissions are dominated by the zodiacal light which is shown superimposed on the data.

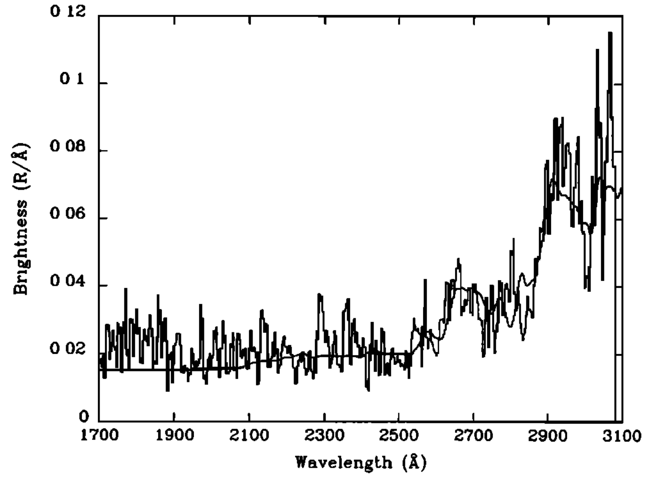

Fig. 5. The spectrum of target 9 when viewing at right angles to the space shuttle velocity vector.

Figure 3. Figure 3 also shows that when not viewing the limb, the long-wavelength emissions tend to be dominated by the zodiacal light. An arbitrarily scaled solar spectrum [*Mount and Rottman*, 1981], smoothed to the instrumental resolution (29 Å), is shown by the smooth line to indicate the shape of the zodiacal light. Figure 4 shows the residuals after the zodiacal light is subtracted. Overlaid on Figure 4 are the locations of the NO bands. Figures 5 and 6 show the same as Figures 3 and 4 for the spectra obtained when viewing perpendicular to the ram. After subtracting the zodiacal light contribution, the upper limits on the long-wavelength band emission were determined by calculating the 3σ uncertainty in the residual counting statistics at the positions of the NO δ, γ, β, O_2 Herzberg bands, and OH $(A^2\Sigma_u^+ - X^2\Pi)(0,0)$ and (1,0) bands. These derived upper limits to the NO δ, γ, β, and O_2 band emissions are 0.6, 0.7, 3.5, and 4.5 R, respectively, for the entire band systems. The upper limit on the OH emission is 0.1 R.

The ram viewing spectrum from the short wavelength monochromator is shown in Figure 7. The spectrum is dominated by O I 1304 and 1356 Å emissions of a few tenths of a rayleigh. Emission at this level is consistent with measurements of the recombination of atmospheric O^+ and electrons [*Brune et al.*, 1978]. Without detailed knowledge of the electron density profile from ionosonde or other sources it is not possible to draw a more definitive conclusion. In Figure 7 the dashed curve is a synthetic LBH spectrum of arbitrary intensity for bands $v' = 0$ to 6 for a temperature of 670 K assuming a thermal N_2 rotational level population. The vibrational distribution has been altered to match the vibrational distribution found by *Conway et al.* [1987] in modelling the S3-4 satellite data which has a maximum at the $v' = 0$ level. This vibrational distribution has been used to set the upper limits on N_2 LBH emission. The rotational lines have been convolved with a 20-Å full width half maximum slit function. The observed spectrum shows no evidence for the presence of the N_2 bands. The spectrum for viewing perpendicular to the ram is shown in Figure 8. Recently, *Torr et al.* [1991] reported that the N_2 LBH emission observed on Spacelab 1 was a factor of 4 higher

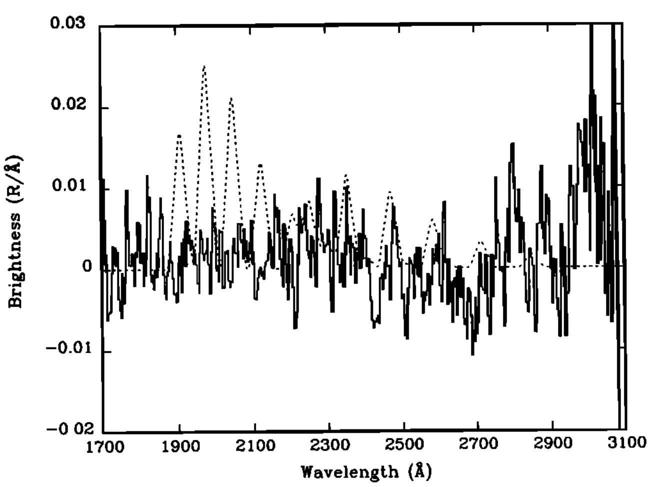

Fig. 4. The spectrum of Figure 3 with the zodiacal light subtracted. A synthetic spectrum of the NO δ, γ, and β bands is shown by the dashed curve.

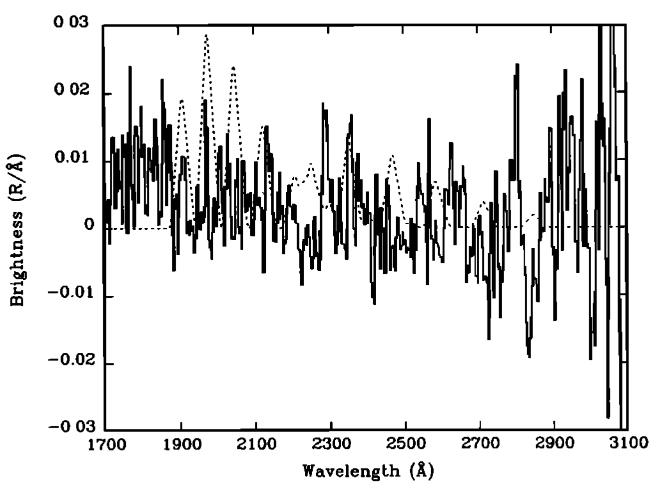

Fig. 6. The spectrum of Figure 5 with the zodiacal light subtracted.

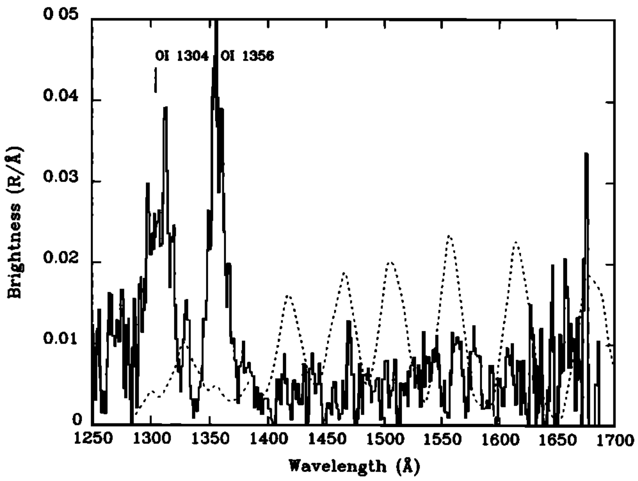

Fig. 7. A short-wavelength (G-tube) spectrum of target 9 viewing into the ram, which is dominated by O I 1304 and 1356 Å emissions produced by recombination of $O^+ + e$. The dashed curve is a synthetic N_2 LBH spectrum plotted at the instrument resolution.

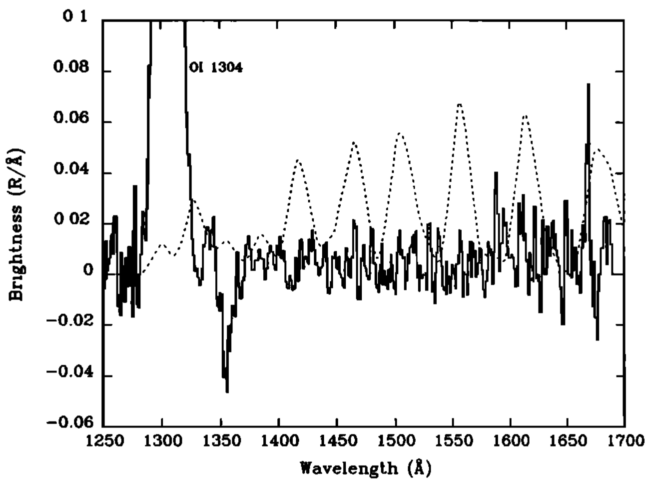

Fig. 9. The difference between the ram viewing (Figure 7) and perpendicular viewing (Figure 8) for target 9. No ram induced effects are apparent.

when viewing perpendicular to the ram direction than when viewing into the ram. We have examined in detail our perpendicular viewing case and set an upper limit of 26 R for this viewing geometry. The upper limit is higher for this case because of a higher dark count rate (6 counts s^{-1}) on this part of the orbit as compared with the dark count rate when viewing into the orbiter ram (3 counts s^{-1}). A difference spectrum between the two viewing geometries is shown in Figure 9 indicating that no N_2 LBH is observed with a 3σ upper limit of 5.3 R for the entire band system and that no ram induced effects are observed.

This result is consistent with a scaling of the Spacelab 1 results to the N_2 density corresponding to 330 km altitude at solar minimum. The Spacelab 1 experiment observed 10–50 R/Å of N_2 LBH under conditions of moderate solar activity and at an altitude of 250 km. The MSIS-86 model N_2 density for these conditions is approximately 4×10^8 cm^{-3} whereas for STS-61C the model N_2 density is approximately 4×10^6 cm^{-3} ($T_\infty = 670$ K). If the N_2 emissions scale as $[N_2]^3$, then

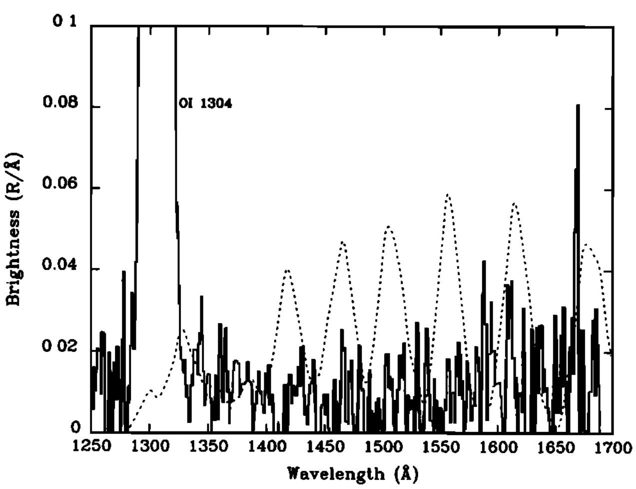

Fig. 8. The spectrum of target 9 viewing perpendicular to the ram. As in Figure 7 the dashed curve is a synthetic N_2 LBH spectrum.

the factor of 100 difference in N_2 densities would correspond to a difference of 100^3 or 10^6 in intensity. This would imply that the UVX experiment would have detected between 5 and 25×10^{-3} R of N_2 LBH, approximately 3 orders of magnitude below the sensitivity of the UVX experiment. If UVX had flown under solar maximum conditions (T_∞ = 1100 K and N_2 density 9×10^7 cm^{-3}) then it is possible it would have detected as much as 235 R of N_2 LBH assuming that the Spacelab 1 experiment conditions represented a typical space shuttle environment.

4. Conclusion

Ultraviolet shuttle glow emission was not detected from the UVX experiment on the space shuttle *Columbia* at 330 km altitude with 3σ upper limits based on counting statistics on N_2 LBH, O_2 Herzberg, and NO δ, γ, and β of 5.3, 4.5, 0.6, 0.7, and 3.5 R of total band emission, respectively. The upper limit on the OH $(A^2\Sigma_u^+ - X^2\Pi)(0,0)$ and (1,0) band emission is 0.1 R. These results are consistent with the recent modelling of spacecraft induced LBH glow mechanisms of *Kofsky* [1988], *Swenson and Meyerott* [1988], and *Cuthbertson and Langer* [1989] and are consistent with a $[N_2]^3$ or $[N_2]^2[O]$ altitude dependence on this emission. The branching ratio of the NO $C^2\Pi$ state to the $A^2\Sigma^+$ state was determined from the UVX experiment by measuring the ratio of the total emission rate from the δ band system to that of the γ band system. Using the best fit for the δ to γ band ratio from the limb viewing data, we found that the branching ratio for the $C^2\Pi$ state to the $A^2\Sigma^+$ state is 0.37 ± 0.03.

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