INTERPRETATION OF THE N_2 LBH GLOW OBSERVED ON THE S3-4 SPACECRAFT

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Abstract

Emissions in the vacuum ultraviolet Lyman-Birge-Hopfield (LBH) bands of N_2 have been observed at night from the S3-4 spacecraft and from the Space Shuttle. No atmospheric source of this emission has been identified. Conway et al. have reported that the intensity of the S3-4 LBH emission varied as the cube power of the N_2 concentration, $[N_2]^3$ or $[N_2]^2[O]$. They suggested a vehicle-atmosphere interaction as the source but found that the needed excitation cross-section would have to be unacceptably large. In this paper we show that recent models of the gas concentration build-up around large space vehicles predict concentrations that may be consistent with the observed LBH intensity variation with altitude. The emission in our model is generated primarily by secondary collisional excitation by ambient N_2 and/or O of desorbed metastable molecular constituents. A Chapman-like production function in the induced gaseous environment results in the observed $[N_2]^3$ altitude variation. A cross section of $\sim 2.5 \times 10^{-18}$ cm^2 is required for excitation of desorbed metastable $N_2(A)$ to the $N_2(a^1\pi_g)$ state to account for the observed intensities.

Introduction

Conway et al. (1987) have reported observations of vehicle induced emission in the Lyman-Birge-Hopfield (LBH) bands of N_2 on the S3-4 spacecraft. The $N_2(a^1\pi_g)$ state, from which the LBH bands arise, requires up to 9.75 eV for its excitation and there is no identified source for these bands in the non-auroral nightglow. Figure 1 reproduces their results for the altitude variation of the integrated band intensities between 1400 and 1700 A for nadir viewing. Conway et al. (1987) report that the intensity varies with altitude as $[N_2]^3$ (or $[N_2]^2[O]$). They show that if the source mechanism is a three-stage excitation process involving the surface, then the expected LBH intensity would be ~16 orders of magnitude short of explaining the observed intensities. Since the observations were made viewing in the nadir direction, this suggests that the source of the glow is a gas-phase reaction. Observations of LBH emission were also observed by Torr et al. (1985) on the Shuttle at night when viewing in the nadir, which again suggests a gas-phase source mechanism. In this paper we utilize the vehicle contamination model of Rantanen et al. (1985) and Rantanen and Gordon (1987) which predicts a significant concentration enhancement of local gases around orbiting vehicles, to investigate the viability of the following hypothesized collisional excitation mechanisms:

$$O^a + N_2{}^s(A^3\Sigma_u{}^+) \rightarrow N_2(a^1\pi_g) + O \qquad (1)$$

or

$$N_2^a + N_2^s\ (A^3\Sigma_u^+) \bullet N_2(a^1\pi_g) + N_2 \qquad (2)$$

followed by

$$N_2(a^1\pi_g) \rightarrow N_2(X^1\Sigma_g^+) + h\nu \qquad (3)$$

Superscripts s and a refer to the spacecraft induced and ambient thermospheric concentrations, respectively. Based on Spacelab 1 observations which indicate enhanced N_2 Vegard Kaplan emission, we suggest below that a significant fraction (~10%) of N_2 desorbed in the contamination model is produced in the $A^3\Sigma_u^+$ state. We therefore predict enhanced N_2 Vegard Kaplan emission without the usual ratio to first and second positive prompt emissions, and this is consistent with the spectral observations made on the Spacelab 1 shuttle mission. For gas phase reactions, the ambient O and N_2 have relative center of mass energies of ~4 and ~5 eV, respectively, which is sufficient to allow collisional excitation of the $N_2(A)$ to the $^1\pi_g$ state. Thus in processes (1) and (2) ambient thermospheric atomic oxygen and molecular nitrogen are hypothesized to collisionally excite the $a^1\pi$ state of N_2, which then radiates in the LBH bands. The gas buildup predicted by the contamination model is discussed below. While such models are yet to be substantiated by measurements, the induced gas enhancement does offer a possible explanation for the observed characteristics of the LBH emission.

Configuration Contamination Model

Recently Rantanen et al. (1985) and Rantanen and Gordon (1987) predicted a significant concentration buildup around the Shuttle and other orbiting vehicles as a result of a non-linear interaction between molecules desorbed from the vehicle surface and the influx of ambient particles with relative velocities of ~8 km s^{-1}. If the gases impacting the vehicle surfaces are thermally accommodated, for surface temperatures near ~300 °K, the desorbed products will have velocities of ~ 5 x 10^4 cm s^{-1}.

To provide a conceptual picture of how the contamination configuration model generates a density enhancement, we consider the following simple argument. The mean free path for a constituent traversing a gas of concentration n is given by

$$\lambda = \frac{1}{n\sigma} \tag{4}$$

where σ is the collision cross-section. The concentration buildup of desorbed gases scales as the ratio of the velocities of re-emitted (v_r) to that of the ambient species (v_a) and λ decreases to

$$\lambda = \frac{1}{n\sigma} \frac{v_r}{v_a} \tag{5}$$

If the re-emitted species are thermalized on the surface, the mean free path decreases by an order of magnitude. The re-emitted species, however, now encounter incoming ambients which further reduces the mean free path. As a result of these

interactions, the mean free path in the contamination buildup near a ram surface at ~200 km is 10 m compared to 1000 m for the undisturbed ambient gas. These results have been independently confirmed by Heuser et al. (1985) who utilized Bird's (1981) Monte Carlo approach.

Rantanen and Gordon (1987) have computed the gas concentration buildup in front of a flat rectangular surface directed with the normal to the surface into the velocity vector. The total ambient concentration used in the calculation was 5×10^9 cm^{-3}, which corresponds to the thermosphere at approximately 200 km for low to moderate solar activity. The results of this calculation are reproduced here as Figure 2a. The enhancement at the surface is considerable and results in a column concentration of $\sim 1.4 \times 10^{14}$ cm^{-2}. The concentration at the surface is 2×10^{11} cm^{-3} which is 40 times the ambient. In addition, Rantanen and Gordon (1987) have modeled the concentration enhancement for such a surface travelling parallel to the velocity vector. Their results for this case are reproduced in Figure 2b. It can be seen from these two figures that while the enhancement along the parallel surface is less than the ram surface, it is still 2 to 3 times the local ambient concentration. However, it appears that the scale length is greater, ~10 m vs 5 m for the ram situation. It is the parallel surface case that would be relevant for comparison with the nadir viewing observations.

The model calculations reported by Rantanen and Gordon (1987) show that the contamination buildup in front of ram surfaces scales approximately linearly with total ambient

concentration and rather insensitiviely to surface area for large (> 1 m) diameters. For example, a surface with a diameter of 14 meters produced an enhancement ~50% greater than one 2 meters in diameter.

The composition of the gas enhancement is dependent on the desorbed surface species, which are in turn dependent on the composition mix of the ambient gas and constituents available for interaction on the vehicle surface.

LBH Glow Mechanism

To explain the observed LBH glow as a gas-phase process requires two key factors: (1) There must be a strong source of metastable electronically excited N_2 in the surface desorption process, so that the $a^1\pi_g$ state can be excited in a single gas phase collision with the 4 to 5 eV available from the ambient O or N_2 in the center of mass system; (2) The processes involved must account for the $[N_2]^3$ or $[N_2]^2[O]$ scaling with altitude.

Green (1984) pointed out that when the thermal contribution to the total energy of the ambient N_2 is taken into account, the nitrogen molecules will have energies with respect to the vehicle surface of 9.3±2 eV, compared with the 9.75 eV required to dissociate N_2. Thus N_2 may dissociate on the surface on impact, with the product N atoms remaining adsorbed on the surface where they may reform into N_2 molecules. The problem is that this process occurs near threshold energy, and might not be rapid. However, the energy partitioning in the interaction of gases with adsorbed atoms has been studied for many years, and it is well

established that several kinds of processes can lead to internal excitation of molecules formed on the surface. Green (1984) mentions Langmuir-Henschelwood and Rideal processes which have been observed to give rise to electronically excited N_2 and O_2 over a variety of surfaces (Mannella and Harteck, 1961). A detailed study of N-atoms has been made by Halpern and Rosner (1982) who have confirmed the production of electronically excited N_2 for various surfaces. In particular, Golde and Thrush (1973) observed recombined N_2 molecules leaving some surfaces in the metastable N_2 ($A^3\Sigma_u^+$) state. Green therefore proposed that atmospheric N_2 can dissociate upon collision with the vehicle surface, producing N atoms which recombine to produce $N_2(A)$ which then leave the surface.

Our mechanism simply requires that a significant fraction of the desorbed N_2 reside in the $N_2(A)$ state, for which the radiative lifetime is ~2 seconds (Shemansky et al., 1971), which is large compared to the residence time of molecules in the contamination "cloud". We suggest that the $N_2(A)$ molecules might be collisionally excited to the $a^1\pi_g$ state by processes (1) and/or (2).

The $[N_2]^3$ altitude dependence of the glow may arise as follows. Let $F_o = n^a v^a$ be the flux of incident ambient O and N_2. The flux which experiences a collision before reaching the surface is given by

$$F = F_o - F_o e^{-\tau} \qquad (6)$$

where τ is the attentuation depth given by

$$\tau = \sigma \int [x]ds \tag{7}$$

where σ is the collision cross-section (assumed for simplicity to be the same for O and N_2) and $\int [x]ds$ is the total column concentration in the gas build-up. The composition of the gas buildup will be mainly desorbed molecules. The column excitation rate is given by

$$I = \sigma' F \int [N_2(A)]ds$$

$$= \sigma' F_o(1 - e^{-\tau}) \int [N_2(A)]ds \tag{8}$$

where σ' is the cross section for collisional excitation of $N_2(A)$ to $N_2(a)$, which we assume to be the same for O and N_2. In the case where $\tau << 1$, that is, for a small gas buildup,

$$I \approx \sigma\sigma'[F_o \int [x^s]ds \int [N_2(A)^s]ds \tag{9}$$

The product of the concentrations, $[O^a + N_2{}^a]$, $[x^s]$ and $[N_2(A^s)]$ lies between $[N_2{}^a]^2\ [O^a]$ and $[N_2{}^a]^3$, since the concentration in the gas buildup scales linearly with the ambient atmosphere according to the Rantanen (private communication, 1987).

For the purpose of this estimate, we will consider the possible enhancement that might be induced for the S3-4 satellite at an altitude of 180 km, by scaling the Rantanen and Gordon

(1987) results accordingly. The total column concentration at 180 km at a surface parallel to the velocity vector is scaled linearly from Figure 2, and is ~2.8×10^{13} cm^{-2}. We will assume that at 180 km, a fraction β (~0.25) ~~of~~ the enhancement is N_2; i.e., ~7×10^{12} cm^{-2} with some fraction α (~0.1) in the A state. It must be emphasized that these values are only estimates and must await empirical verification. The incident O and N_2 flux at 180 km is 6×10^{15} cm^{-2} s^{-1}. The total ambient concentration at 180 km is 1.15×10^{10} cm^{-3}.

We will now consider the collisional excitation of the N_2 molecules in the enhancement region by the relatively energetic flux of ambients. The column production of $N_2(a^1\pi_g)$ using equation (8) becomes

$$I = \alpha\beta\sigma\ \sigma'\ F_o(\int [x^s]ds)^2 \qquad (10)$$

where $\int [x^s]ds$ is 2.8×10^{13} cm^{-2}.

If we assume that all of the $N_2(a)$ produced radiates in the LBH bands, we can solve (10) directly for the effective collisional excitation cross-section required to explain ~600 R of LBH emission observed by S3-4 at 180 km.

$$\sigma' = I/[\alpha\beta\sigma F_o(\int [x^s]ds)^2] \qquad (11)$$

$$\approx 2.5 \times 10^{-18}\ cm^2$$

where we assume $\sigma = 2 \times 10^{-15}$ cm^2. The excitation collision cross-section inferred above may not be unreasonable for all the LBH

bands lying between 1400 Å and 1700 Å since in this case the target resides in an exicted state which may require a smaller corss-section than for excitation from the ground state. The scale height of the emission will be $\sim[N_2]^3$ for reaction (1) and (2) in agreement with the observations of Conway et al. (1987).

Conclusion

We have demonstrated that if the concentrations predicted by the configuration contamination model of Rantanen et al. (1985) are accepted, then it is possible to explain the LBH glow observed by the S3-4 satellite in terms of collisional excitation of metastable $N_2(A)$ to $N_2(a^1\pi_g)$ in the vehicle induced gas cloud by the incoming flux of atmospheric neutrals. The contamination model predicts a significant column concentration of desorbed N_2 near nadir surfaces and our proposed mechanism requires a significant fraction (~10%) residing in the $N_2(A)$ state. The desorbed $N_2(A)$ in the induced enhancement is then collisionally excited by the relatively energetic ambient N_2 and or 0. The result is an induced LBH emission that will vary approximately as $[N_2]^3$. The required excitation cross-section is 2.5×10^{-18} cm^2.

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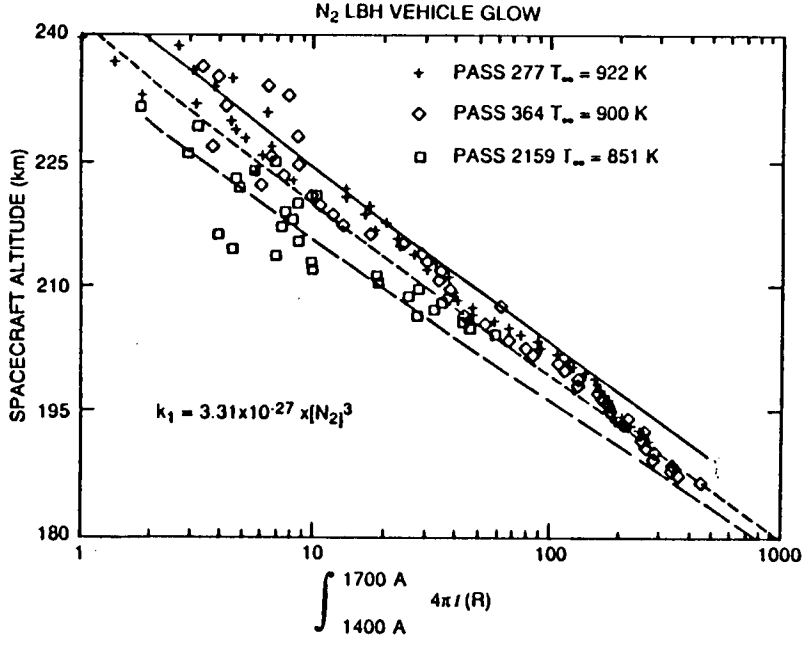
Figure Captions

Fig. 1. Total intensity in Rayleighs between 1400Å and 1700Å vs spacecraft altitude compared to MSIS-83 densities of molecular nitrogen. The product of the cube of the N_2 density and the factor 3.31×10^{-27} Rayleighs cm^9 for the three passes are shown by the solid, dotted and dashed lines. (From Conway et al. [1987]).

Fig. 2. Isocontours of concentration enhancement predicted by the contamination model: (a) normal to plane surface into velocity vector; (b) plane surface parallel to velocity vector. (From Rantanen and Gordon, 1987).


N_2 LBH VEHICLE GLOW
PASS 277 T_∞ = 922 K
PASS 364 T_∞ = 900 K
PASS 2159 T_∞ = 851 K
$k_1 = 3.31 \times 10^{-27} \times [N_2]^3$
SPACECRAFT ALTITUDE (km)
240
225
210
195
180
1
10
100
1000
$\int_{1400\ A}^{1700\ A} 4\pi I(R)$

F19

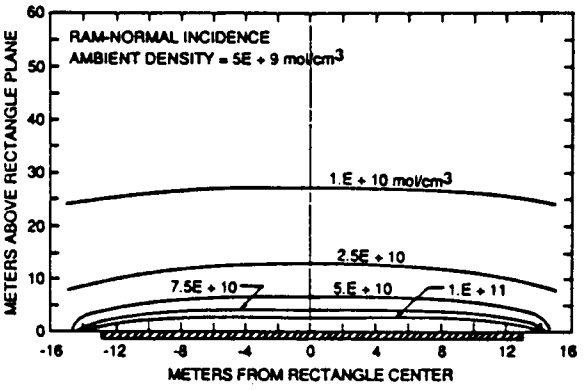

RAM-NORMAL INCIDENCE
AMBIENT DENSITY = 5E + 9 mol/cm3
1.E + 10 mol/cm3
2.5E + 10
7.5E + 10
5.E + 10
1.E + 11
METERS ABOVE RECTANGLE PLANE
METERS FROM RECTANGLE CENTER
60
50
40
30
20
10
0
-16
-12
-8
-4
0
4
8
12
16

FIG 2

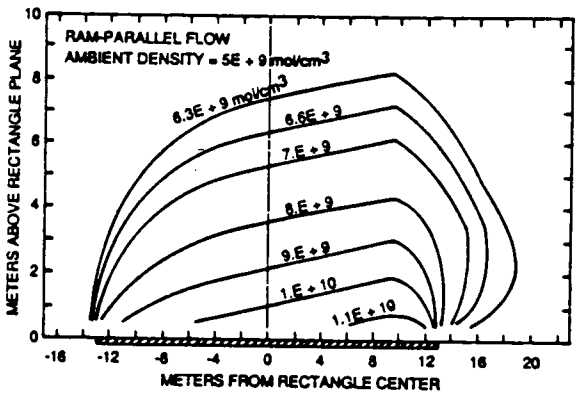

RAM-PARALLEL FLOW
AMBIENT DENSITY = 5E + 9 mol/cm3
6.3E + 9 mol/cm3
6.6E + 9
7.E + 9
8.E + 9
9.E + 9
1.E + 10
1.1E + 10
METERS ABOVE RECTANGLE PLANE
METERS FROM RECTANGLE CENTER
10
8
6
4
2
0
-16
-12
-8
-4
0
4
8
12
16
20

FIG 3