Radiative Lifetime Analysis of the Shuttle Optical Glow

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Photographs taken during the third flight of the Space Shuttle revealed the presence of a diffuse optical glow above the surfaces of the vehicle in the ram direction. The origin of the glow is unknown but is clearly a manifestation of the interaction of the spacecraft with the ambient atmosphere. The line-of-sight intensity is found to be approximately three times more intense than the airglow seen at the limb of the Earth. We assume that the glow is produced by excited molecules created in a chemical reaction at the surface, which leave the surface isotropically. By analyzing the spatial distribution of the glow, we obtain a characteristic decay length of 20 cm. The corresponding radiative lifetime depends on the velocity with which the species leaves the surface. For a velocity within a factor of 2 of the thermal velocity, the derived radiative lifetime lies between 0.3 and 1.3 ms. The production efficiency for the visible Shuttle glow is 2.5×10^{-6} photons per impacting oxygen atom. The species responsible for the Shuttle glow and the Atmosphere Explorer satellite glow appear to be different.

I. Introduction

NIGHTTIME photographs taken by the crew of the STS-3 mission revealed an optical emission of unknown origin appearing above parts of the Orbiter surface in the ram direction of the vehicle. Figure 1 is a nighttime photograph of the STS-3 payload bay, showing the vehicle glow above the surfaces of the vertical stabilizer and the engine pod. The airglow emissions from altitudes of about 100 km are visible in the background. The emission has an intensity comparable to that of the airglow emission seen at the limb of the Earth[1] and may limit the sensitivity of optical and infrared astronomical and aeronomical experiments planned for future Space Shuttle missions.

A similar emission has beem observed by photometric measurements onboard other spacecraft.[2-4] Torr et al.[2] noticed some unexplained enhancements in the airglow intensities measured by the Visible Airglow Experiment (VAE) onboard the Atmosphere Explorer-C satellite,[5] which they attributed to some form of interaction between the satellite and the atmosphere. After correcting the VAE measurements for the galactic background and atmospheric emissions, Yee and Abreu[3,4] substantiated the finding of Torr et al.[2] and demonstrated that the intensity of the interaction-induced glow is proportional to the density of the ambient atomic oxygen atoms. They attributed the emission to collisions of oxygen atoms with the satellite surface in which metastable molecules are formed. The metastable molecules leave the surface and radiate, producing the spatially extended glow.

The identities of the metastable molecules are uncertain, and the processes leading to their production are not fully understood. Yee and Abreu[6] showed that the AE optical glow has a diffuse band spectrum that ranges from the near ultraviolet to the near infrared and probably peaks in the red or in the infrared. Slanger[7] pointed out that the OH airglow emissions in the spectral regions around 7320 and 6563 Å have the same relative intensity as the AE glow and argued that OH is a plausible candidate for the emitter. A more extensive comparison by Langhoff et al.,[8] which used spectral data over a wider range of wavelengths and which is based on a different model of the excitation mechanism, provided support for the OH identification. An alternative theory attributes the glow to impact excitation of some unidentified species by fast electrons created by plasma wave interactions.[9]

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The radiative lifetime of the emitting species can be inferred from the spatial distribution of the glow intensity. From an analysis of the AE data, Yee and Abreu[4] obtained an upper limit of 10^3 cm for the product of the radiative decay time and the velocity of the emitting species. For thermal velocities, the corresponding radiative lifetime has an upper limit of 10^{-2}s, which is consistent with the calculated lifetimes of OH ($X^2\Pi$) for the vibrational levels that contribute to the AE glow observations.[8]

The Shuttle glow has a diffuse spectral component in the wavelength region between 6300 and 8000 Å.[10] Whether the same excited molecules are responsible for the Shuttle and AE glows is a question of considerable interest. In this paper we present a method for analyzing the spatial distribution of the Shuttle glow and determining the radiative lifetime of the emitting species after it departs from the Shuttle surface. We also give estimates of the intensity of the Shuttle glow and of the production efficiency for each atomic oxygen impact.

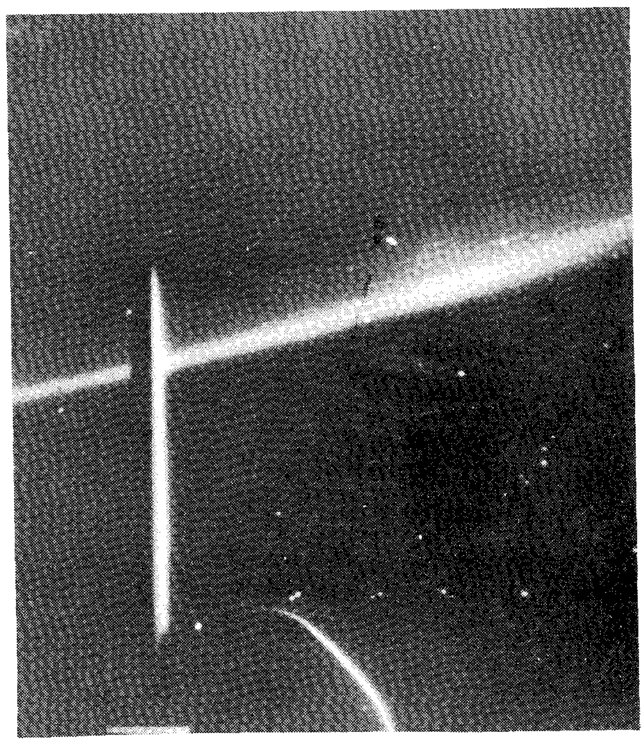

Fig. 1 A nighttime photograph of the STS-3 payload bay.

II. Radiative Lifetime Analysis Technique

Suppose the excited molecules have a radiative lifetime and leave the spacecraft surface with velocity V. The number density $n(x, y, z)$ at a point P' in a Cartesian coordinate system is given by

$$n(x,y,z) = \iiint f(P',\ V')\,V'^2 \mathrm{d}V' \sin\theta \mathrm{d}\theta \mathrm{d}\phi \qquad (1)$$

where $f(P',\ V')$ is the distribution function of the excited molecules in a spherical coordinate system with origin at P'. The geometry is illustrated in Fig. 2.

According to Liouville's theorem, the distribution function $f(P',\ V)$ outside the surface is related to the distribution function of $f(P',\ V)$ at the surface by

$$f(P',\ V') = f(P,\ V) \qquad (2)$$

To include the effect of radiative decay the equation is modified, taking the form

$$f(P',\ V') = f(P,\ V)\exp(-\ |S|/V\tau) \qquad (3)$$

where $|S|$ is the distance between P' and the source point P, provided that the velocity changes little in moving from P to P'. The number density at point P' can then be calculated from

$$n(x,y,z) = \iiint f(P,V)\exp\left(-\ \frac{|S|}{V\tau}\right) V^2 \mathrm{d}V \sin\theta \mathrm{d}\theta \mathrm{d}\phi \qquad (4)$$

After transforming from the spherical coordinate system at P to the Cartesian coordinate system at O, we obtain

$$n(x,y,z) = \iiint f(P,V)\exp\left(-\frac{|S|}{V\tau}\right) V^2 \mathrm{d}V(\boldsymbol{n}\cdot\boldsymbol{S}/\ |S|^3)\mathrm{d}A \quad (5)$$

where $\mathrm{d}A$ is the spacecraft surface element, $\boldsymbol{n}$ is the unit vector normal to the surface, and the term $\boldsymbol{n}\cdot\boldsymbol{S}/\ |S|^3\ \mathrm{d}A$ is the element of solid angle $\mathrm{d}\Omega = \sin\theta \mathrm{d}\theta \mathrm{d}\phi$ subtended by $\mathrm{d}A$ at the position P'. Consistent with our model of a surface reaction, we assume that the excited molecules leave the surface isotropically. If their speed is V_0, the equation can be rewritten as

$$n(x,y,z) = V_0^2 \int f(P,V)\exp\left(-\ \frac{|S|}{\ell}\right)(\boldsymbol{n}\cdot\boldsymbol{S}/\ |S|^3)\mathrm{d}A \qquad (6)$$

where ℓ is the characteristic decay length defined as the product of the velocity and the radiative lifetime of the excited molecules.

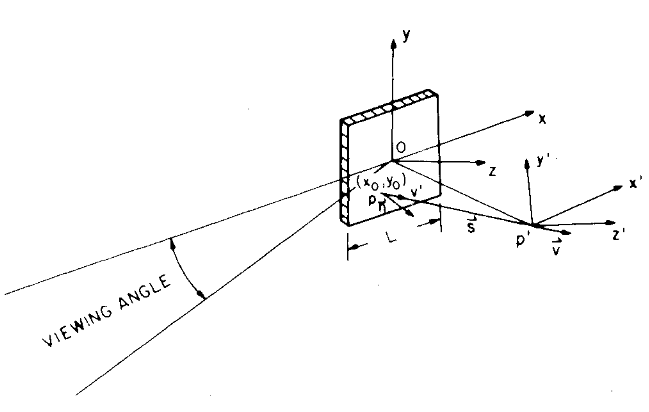

Fig. 2 The geometry used for the spatial distribution of the excited molecules.

The glow intensity is a column-integrated emission rate given by the product of the inverse of the lifetime and the column density obtained by integrating along the line of sight. It varies with the orientation of the spacecraft surface relative to the streaming ambient atmospheric particles.[1,4] Hence, the source distribution $f(P,V)$ at the surface may not be a spatially uniform function and, in performing the integrations, the dependence on the angle of incidence must be considered.

For a flat spacecraft surface, however, the angles between the surface normal and the velocity vector are the same everywhere at the surface, giving rise to a spatially uniform source function $f(p,V)$. From the Shuttle glow picture (Fig. 1), it appears that the right side of the stabilizer was facing the streaming ambient particles when the picture was taken and a flat surface can be adopted for our analysis.

III. Example for a Spacecraft Surface with a Square Cross Section

Before analyzing the Shuttle glow picture, we consider as an example a spacecraft surface of square cross section of dimension L. The number density of the excited molecules at point P' is calculated in this case from

$$n(x,y,z) = n_0 \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} \exp\left(-\frac{|S|}{\ell}\right)(\boldsymbol{n}\cdot\boldsymbol{S}/\ |S|^3)\mathrm{d}x_0 \mathrm{d}y_0$$

where

$$\boldsymbol{S} = (x-x_0)\boldsymbol{i} + (\ y-y_0)\boldsymbol{j} + (z-z_0)\boldsymbol{k}$$

and $\boldsymbol{n} = \boldsymbol{k}$.

Figure 3 presents curves of constant n/n_0 ratio, showing the number density spatial distribution at $y=0$ for the case when the characteristic decay length ℓ is taken equal to L, the dimension of the surface. A plume shape distribution is obtained, with the number density peaking at the center, $x=0$. In general, the number density at a point outside the surface is determined by the solid angle subtended by the surface, modified by the radiative lifetime τ.

Along the z axis, where $x=0$ and $y=0$, if the characteristic decay length is long compared to the dimension of the spacecraft ($\ell \ll L$), the number density is controlled by the solid angle term and decreases like $1/z^2$. If $\ell \ll L$, the number density decreases with z with an e-folding distance close to the characteristic decay length. Figure 4 shows the calculated line-of-sight intensities as viewed along the x axis for various choices of ℓ. By comparing the calculated spatial variation with the observed, we can infer the characteristic decay length of the excited molecules. The results we present are all given

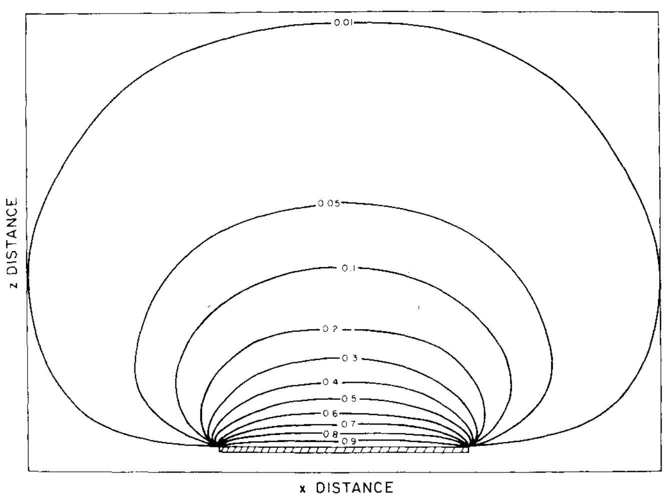

Fig. 3 Curves of constant-number density above the surface of a square cross section.

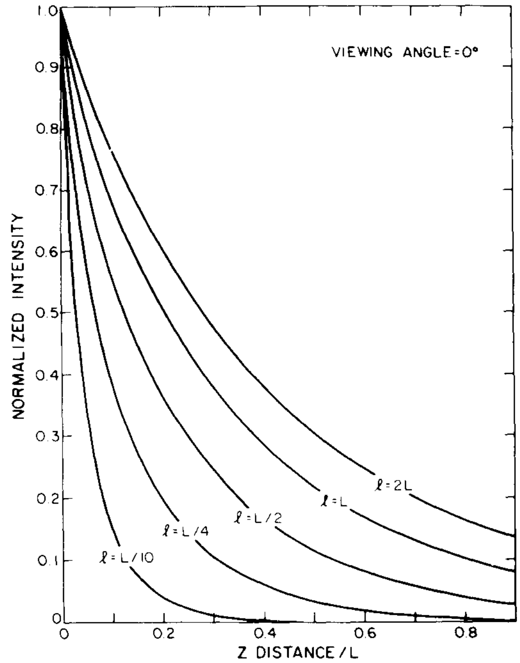

Fig. 4 Calculated line-of-sight intensity spatial distribution viewed along the x axis for various choices of ℓ.

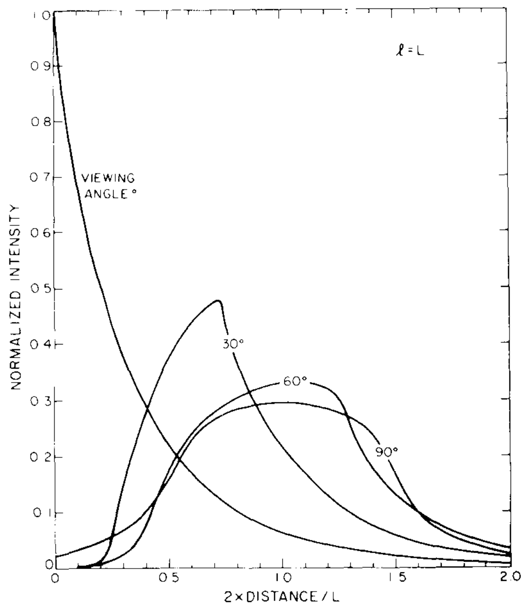

Fig. 5 Calculated line-of-sight intensity spatial distribution for different viewing angles.

on a relative scale. The absolute e-folding distance deduced from the shape of the observed spatial distribution gives rise to different characteristic decay lengths for different sizes of the spacecraft surface.

The spatial distribution of the glow intensity is predicted to depend strongly on viewing direction. Figure 5 shows the calculated results at four different viewing angles for the case of $\ell = L$. The maximum line-of-sight intensity decreases as the viewing angle increases and the glow appears to extend to a farther distance as if a longer radiative lifetime were involved. Consequently, in analyzing the measured spatial distribution of the glow intensity to infer the magnitude of ℓ, the viewing direction, as well as the size and the shape of the spacecraft, must be taken into account.

Fig. 6 A picture of the Shuttle glow. Owing to the rotation of the Orbiter, stars are seen as streaks.

IV. Shuttle Stabilizer Glow Analysis

Figure 6 is a picture of the glow obtained during the same mission. All the photographs were taken from the aft flight-deck observation wind using a bracket-mounted 70-mm Hasselblad camera. The pictures we present here were originally in color and taken with Kodak Ektachrome SO-489 film and developed to achieve an exposure index of ASA 400.[1] We have used an image-processing facility consisting of an International Imaging System model 70F Image Computer and color display terminal to digitize the photographs of the glow and obtain in numerical form the spatial distribution of the glow intensity.

Figure 7 presents the results obtained after digitizing the picture of Fig. 6. It shows the variation of the glow intensity with distance along a chosen axis. The intensity counts can be adjusted by the system gain, becoming saturated when the counts reach 256 (8-bit system). In Fig. 7 the gain has been adjusted so that the best signal-to-noise ratio is obtained. The surface of the stabilizer facing the streaming ambient particles is made of two nearly flat surfaces intersecting at an angle close to 168 deg. Because of the location of the flight-deck window, the maximum glow intensity occurs along the intersecting line of the two flat surfaces of the stabilizer.

Figure 8 plots the intensity spatial variation obtained after subtracting the background counts as a function of distance along the chosen axis. The extent of the glow is estimated from the known size of the vertical stabilizer. The glow intensity has an apparent maximum at about 20 cm and decreases to the noise level at approximately 45 cm with an e-folding distance of 12 cm. By comparing it with the theoretically calculated spatial variations, we could infer the characteristic decay length of the excited molecules when they leave the surface. Uncertainties occur in using the procedure because the digitized intensity is not the real glow intensity. The luminosity sensitivity of the SO-489 film, the film processing and developing techniques, and the system gain adjustments of the imaging procedure cause a nonlinear correspondence between

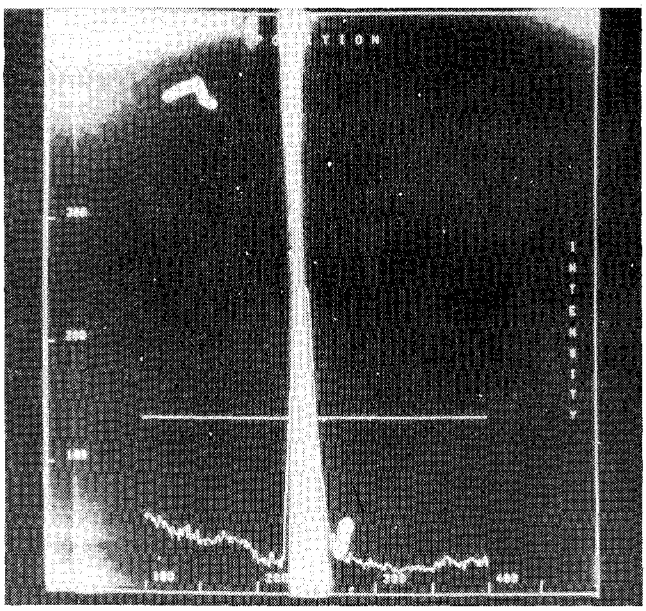

Fig. 7 Digitized glow intensity as a function of distance along a chosen axis.

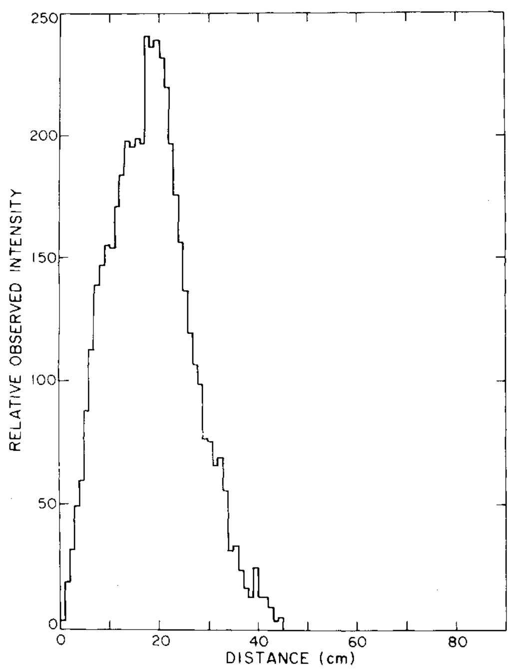

Fig. 8 Background-corrected glow intensity as a function of distance.

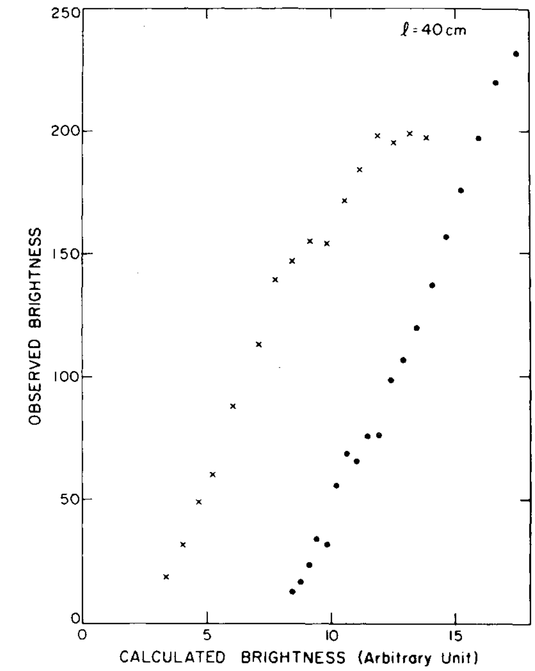

Fig. 9 The digitized and the model calculated intensities for $\ell = 40$ cm.

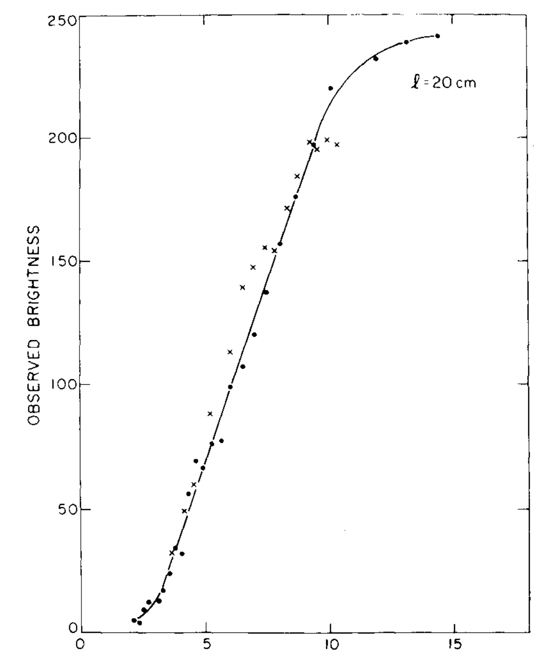

Fig. 10 As for Fig. 9 with $\ell = 20$ cm.

the digitized intensity and the actual glow intensity. We present an alternative approach that avoids these difficulties.

Figure 9 plots the intensities observed at various distances from the surface vs the model values for a characteristic decay length ℓ of 40 cm. The dots represent the observations viewed at distances greater than 20 cm, and the crosses represent those at distances less than 20 cm. Theoretically, the dots and crosses should lie on the same curve, no matter what the processing procedures are. It is clear from Fig. 9 that the choice of 40 cm as the characteristic decay length is not correct.

As demonstrated in Fig. 10, we found that the best agreement is obtained when the characteristic decay length is chosen to be 20 cm. That the derived decay length coincides with the distance at which the glow achieves its maximum intensity (Fig. 8) is an accident of geometry. For a decay length of 20 cm, Fig. 10 shows that the measured and the calculated intensities have a linear relationship except in the high- and low-exposure regions. The relationship is quite similar to the granular density-log-exposure curve of the Kodak SO-489 film (Fig. 11) used in the photograph. Differences occur because the film developing techniques and the system gain adjustment during the imaging processes distorted the curve we derived.

We have ignored the contribution to the glow from reflection. Reflection will modify the brightness distribution close

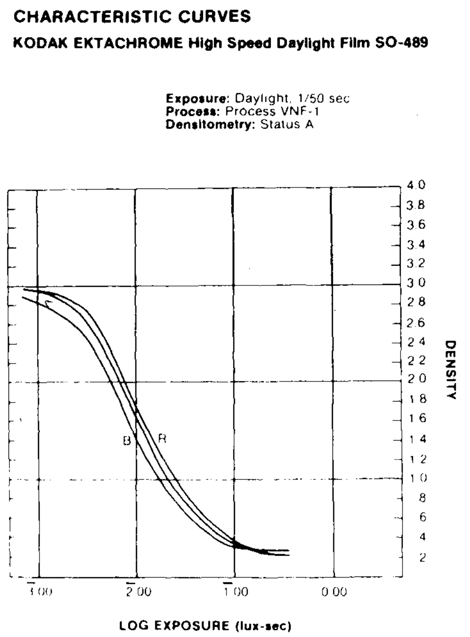

Fig. 11 The characteristic log-exposure curves for Kodak SO-489 film.

to the surface, but the outer region of the profile shown in Fig. 8 will be relatively unaffected. The close agreement at all distances beyond 5 cm demonstrated in Fig. 10 suggests that reflection is not important in our analysis so that, given our surface chemistry model, 20 cm is a reliable estimate of the decay length.

There is evidence of a thruster firing during the exposure of Fig. 6. We have analyzed another exposure of the glow during which no thruster firing occurred. We again derived a decay length of 20 cm, and we believe that thruster firing did not enlarge the spatial extent of the glow after the initial enhancement had dissipated.

The velocity with which the postulated metastable species departs from the surface is unknown. If we assume that it is within a factor or two of thermal value of 300 ms^{-1}, the derived lifetime lies between 0.3 and 1.3 ms. Our estimate is consistent with that of Banks et al.,[14] who used a less detailed analysis to infer a lifetime of 0.3 ms from their observations on STS-8.

V. Discussion and Conclusions

Recent photometric and photographic observations have revealed the presence of induced optical emissions over the surface of the spacecraft due to the interaction of the spacecraft and the ambient atmosphere. Radiative emission from some unknown excited molecules formed on the spacecraft surface may be responsible for the observed luminosity. In this paper we have presented a method for inferring the radiative lifetime of the excited molecules by analyzing the spatial distribution of the observed intensity. We have demonstrated that the observed intensity spatial distribution depends on the shape and size of the spacecraft surface, the spacecraft orientation, and the radiative decay length of the excited molecules.

By examining the extent of the glow from the photographs, we have obtained a characteristic decay length of 20 cm for the Shuttle glow. The decay length is an important parameter in determining the identities of the emitting excited molecules and their formation processes. The photometric data analysis suggests that the OH Meinel band system is largely responsible for the glow observed at high altitudes on the AE satellites[7,8] and a high-resolution spectrum obtained by the Fabry-Perot Interferometer onboard the Dynamic Explorer (DE)-B satellite is consistent with the OH hypothesis.[11] The radiative lifetime inferred from the Shuttle glow picture is much shorter than the OH ($X^2\Pi$, v) radiative lifetimes,[8,12] suggesting that some other excited species besides OH is producing the Shuttle glow. Recent studies support the identification of the emitting species as NO_2.[13,14] Whatever the origin of the Shuttle glow, the mechanism may also contribute to the Atmospheric Explorer glow.[15]

The intensity of the Shuttle glow can be estimated by comparing it with the airglow feature seen at the limb of the Earth. Mende et al.[16] analyzed the airglow emission spectrum using a low-resolution grating spectrometer aboard STS-5 and identified several of the emission features including the 5577 Å line, the OH Meinel bands, and the atmospheric O_2(O-O) band. The atmospheric hand at 7619 Å was found to be the brightest emission seen from space. The horizontal emission intensity was estimated to be 200–300 kR. After digitizing the picture, we found that the maximum glow intensity is about three times more intensive that the airglow, giving for the Shuttle glow an estimated intensity of about 750 kR. From our theoretical calculation, a line-of-sight column intensity of 750 kR corresponds to a maximum volume emission rate of 1.8×10^8 photons $cm^{-3}s^{-1}$, or a number density of $1.2 \times 10^5 cm^{-3}$ at the surface. The incoming flux of atomic oxygen at the Shuttle altitude is about 1.4×10^{15} atoms $cm^{-2}s^{-1}$, so that the production efficiency is 2.5×10^{-6} excited molecules per impacting oxygen atom. The total production for a seven-day period is $3 \times 10^{14} cm^{-2}$. The actual efficiency and production may be higher because only visible photons were recorded and some fraction of the excited molecules may radiate in the infrared.

Acknowledgments

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