Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirments are the same as for regular contributions (see inside back cover).

Spacecraft Glow

Harold A. Papazian*
Martin Marietta Aerospace, Denver, Colorado

Introduction

THE ram glow associated with various Space Shuttle flights has been discussed[1] since its discovery on STS-3. Although the glow was not predicted in advance of flight, it has been suggested that it could be associated with the glow of satellites such as the Atmospheric Explorer.[2] The glow from the Atmospheric Explorer (AE) has been examined in considerable detail,[3] and this information is used here to compare its brightness with that of the Shuttle.

The Space Shuttle observations have reported[4] glows associated with the thruster firings. The decay of this glow is analyzed here to indicate a mechanism for the decay.

Results

From the brightness as a function of wavelength data for the AE (see Fig. 3, in Yee and Abreu[3]), the total brightness between 4278 and 7320Å can be estimated. For 170–175 km, this is estimated to be 9.6 kR. On AE the brightness was also determined as a function of altitude (see Fig. 1, in Yee and Abreu[3]). The brightness decreases as the altitude increases. From the constancy of the slope above 160 km, as well as the constancy of the spectral distribution at the two altitudes depicted in Fig. 3 of Ref. 3, it is reasonable to assume a constancy of spectral distribution with altitude for AE. With this assumption, the total brightness, B, between 4278 and 7320Å at any altitude above 170 km may be estimated by

$$\text{Total } B \text{ at altitude} = \frac{B \ @ \ 7320\text{Å at altitude}}{B \ @ \ 7320\text{Å at 170 km}} \times \text{total } B \text{ at 170 km}$$

From Fig. 1 of Yee and Abreu,[3] the brightness at 170 km is estimated as 180 R and at 200 km it is 75 R. Thus, at 200 km this becomes total $B = (75 \text{ R}/180 \text{ R})9.6 \text{ kR} = 4 \text{ kR}$. For comparison of the AE's luminosity with the flat surface of the stabilizer of the Shuttle, Dalgarno et al.[5] suggest a correction of a factor of 2 for the AE surface curvature and a factor of 3 for the AE photometer protrusion. Thus, at 200 km the total brightness for comparison with the Shuttle becomes $4 \text{ kR} \times 6 = 24 \text{ kR}$. Several points calculated in this manner have been plotted here in Fig. 1 as a function of altitude. Glow results from Shuttle flights STS-3, -5, -8, and -41G are also presented in Fig. 1.

Received Oct. 3, 1986; revision received Jan. 10, 1987.

*Departmental Research Scientist, Payloads, Sensors, and Instruments.

For the Shuttle, the characteristic length across the vertical stabilizer and the e-fold of the glow is usually taken as 900 cm and 20 cm, respectively.[6] For STS-8, the brightness (R/Å) at four wavelengths between 5577 and 7600Å has been determined by Kendall et al.[7] From this data the total brightness over the 900 cm of the vertical stabilizer of the Shuttle is estimated to be 665 kR. In the ram direction the extent of the glow is about 20 cm from the stabilizer, and to be comparable to AE, a photometer viewing normal to the stabilizer would see a column length of about 20 cm. Therefore, the total glow (for comparison) is approximately $(20/900)665 \text{ kR} = 14.6 \text{ kR}$, and this is the point labeled as STS-8 in Fig. 1. Brightness at four wavelengths has also been determined[8] for STS-41G. In a similar manner, the estimated total brightness for STS-41G at 230 km is 4.6 kR, and at 360 km it is 1.9 kR. These points are so labeled in Fig. 1.

For STS-3, Yee and Dalgarno[9] estimate the Shuttle glow to be about three times the Earth airglow appearing in the background of the photographed Shuttle glow. They take the airglow to be 10 kR, which is only the atomic oxygen airglow at 5577Å (Banks et al.[1]). This severely underestimates the photographed airglow since it consists of all radiating species and not just atomic oxygen. The airglow has a brightness of 100 kR,[1] and, thus, the correct brightness for STS-3 should be about 300 kR. With the correction for column length, the glow is estimated as $(20/900)300 \text{ kR} = 6.7 \text{ kR}$, which is the point plotted in Fig. 1. By comparing the glow photograph from STS-3 with the photograph of STS-5, Mende and Swenson[4] estimate the glow to be about 1/3.5 times that on STS-3. (Both photos were made with the same camera/film system and with

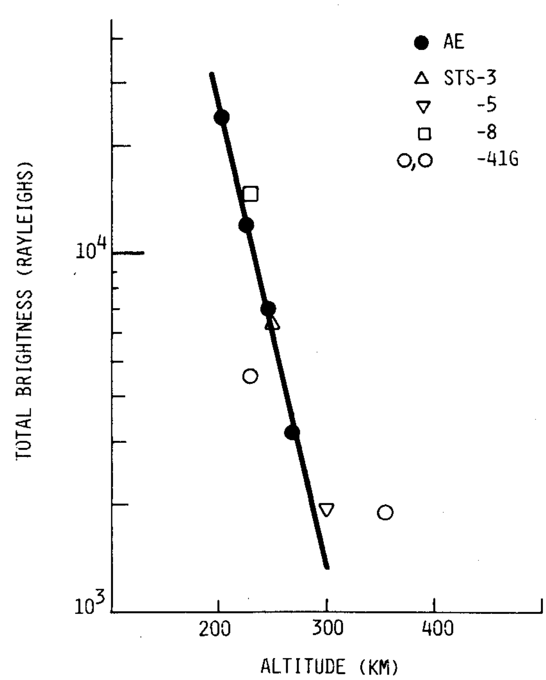

Fig. 1 Comparison of Shuttle glow with AE glow.

similar velocity vectors of the Shuttle.) This estimate for STS-5 is also included in Fig. 1.

Since the most abundant constituents in the ramming atmosphere are OI and N_2, the first suggestion that spacecraft glow could be caused by a NO and O recombination was made by Torr[10] for the emissions observed on the AE-E satellite. In a detailed comparison of the continuum emission from the Shuttle and emission from electronically excited NO_2, Swenson et al.[11] "strongly suggest" that the Shuttle glow is a result of the NO_2 recombination continuum. Reference 11 should be consulted for details of this conclusion, where it is pointed out that temperature effects may be responsible for alternations of observed spectra. Recently in a discussion[12] of the effects of various materials on glow, it has been suggested that the glow is probably due to surface catalytic phenomena.

Even with such potential variants, the results depicted in Fig. 1 show remarkably favorable agreement between AE and Shuttle glow, indicating essentially the same phenomena for both spacecraft.

Thruster firings on the Shuttle create a great deal of observable light, and there is a marked enhancement of the glow on the engine pods. A collage of television monitor photographs has been published,[4] along with the integrated video signal plotted by a chart recorder for STS-3 and -8. The video trace figures were photo-expanded and the decay of the glow, beginning at time $t = 0$, was analyzed. The analysis for STS-8 is depicted in Fig. 2. The analysis for STS-3 is similar but, of course, with different time constants. The analysis for both flights shows two decays, both of which are first order (in chemical kinetics terminolgy) where the rate of reaction of $dx/dx = kx$, i.e., proportional to the first power of the concentration of the reacting species. For STS-8, the time constants, k, are $0.77\ s^{-1}$ and $0.16\ s^{-1}$, and for STS-3, $6.9\ s^{-1}$ and $1.7\ s^{-1}$. The television photographs[4] show a large glow obviously taking place in the gas phase with a rapid decay and a more persistent glow on the engine pods. Thus, in Fig. 2 the more rapid decay ($k = 0.77\ s^{-1}$) can be associated with the gas phase glow decay, and the slower decay can be associated with the surface glow decay. Similar considerations hold for the results for STS-3. It can be noted that the time constants on STS-3 (240 km) are about 10 times those for STS-8 (220 km). An understanding of this can be obtained from the following considerations. The gas phase glow cannot be a simple quenching of an excited species, C^*, from the thruster that decays spontaneously, i.e., $C^* \rightarrow C = h\nu$. If this were so, then the rates of decay should be independent of altitude, depending only on the luminescence lifetime of C^*. It cannot be quenching of an excited C^* from the thruster by a second body, i.e., an ambient constituent, A, by a reaction such as $A + C^* \rightarrow A + C + h\nu$. If this were so, then the time constant of STS-8 at the lower altitude would be larger than that for STS-3 at the higher altitude where the number density of A is smaller. It is known from laboratory studies that time constants for quenching excited species are proportional to the number density of the second body.

Most probably, the glow arises from a neutral specie from the thruster reacting with an ambient specie $A + C \rightarrow h\nu$. Such reactions have been studied with respect to the creation of ionospheric "holes" (i.e., depletion of atomic oxygen and electrons) due to rocket firings.[13] Consider a possible reaction of the type

$$A + C \underset{k_2}{\overset{k_1}{\rightleftharpoons}} [AC]^* \xrightarrow{k_3} h\nu \tag{1}$$

For such a reaction, it can be shown[14]

$$\text{Rate of reaction} = k_3[AC]^* \approx (k_1k_3/k_2)C = kC \tag{2}$$

which is directly proportional to the concentration of C and is of first order in $[AC]^*$, just as found in Fig. 1 (and for STS-3).

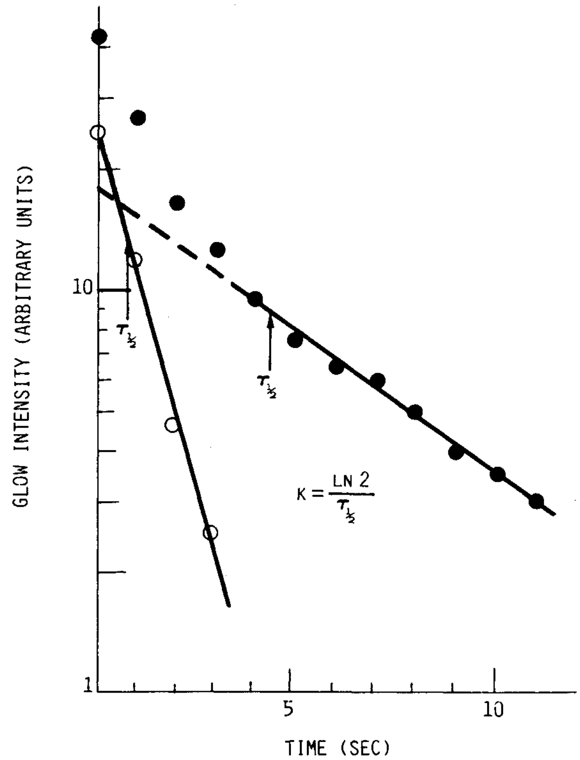

Fig. 2 Analysis of thruster glow of STS-8.

The time constant determined by analysis in Fig. 2 is, thus, composed of several k's and should not be considered as a lifetime of $[AC]^*$. For the suggested reaction, k_2 would be associated with a vibrational coordinate and will most probably be much larger than k_3. Further speculation here is not warranted. However, from the experimental k's it is instructive to consider what the rate of reaction at 220 km would be at 240 km. This normalization leads to

$$\frac{(k_1k_3/k_2)_{220}C_{220}}{(k_1k_3/k_2)_{240}C_{240}} = \frac{(kC)_{220}}{(kC)_{240}} = 1 \tag{3}$$

From Fig. 16 of Mende and Swenson,[4] it can be noted that the burning time at 220 km is about 10 times longer than the time at 240 km. Then, it is reasonable to assume that the concentration of C at 220 km is 10 times the concentration of C at 240 km or $C_{220} = 10\ C_{240}$. Insertion of the appropriate values into Eq. (3) gives $(0.77)\ 10\ C_{240}/6.9\ C_{240} = 1.12$, or very nearly 1 as required by Eq. (3). This result is an ex post facto justification for the concentration assumption made for the two altitudes.

Consider now the slower surface associated glow decay where at 200 km, $k = 0.16\ s^{-1}$ and at 240 km, $k = 1.69\ s^{-1}$. It is reasonable to assume that adsorption of the ambient, A, exists on the surfaces of the spacecraft, and thruster specie C arriving at the surface reacts with the adsorbed material to produce the glow. The kinetics of such a heterogeneous reaction (of two gases on a surface) is given by[4]

$$\text{Rate of reaction} = k(P_C/P_A) \tag{4}$$

where P_A is the pressure or number density of A adsorbed on the surface and P_C is that for the thruster effluent. Equation (4) is, thus, the rate of formation of the excited specie $[AC]^*$ on the surface and for a stationary concentration of $[AC]^*$ is equal to the rate of decay of $[AC]^*$. The glow decay is, therefore, controlled by the slowest step in the reaction, i.e., the formation of $[AC]^*$ on the surface. This is first-order kinetics in C as required by the results of Fig. 2. Normalizing as before for the gas phase leads to

$$\frac{(kP_C/P_A)_{220}}{(kP_C/P_A)_{240}} = 1 \qquad (5)$$

From the burning time, as for the gas phase reaction, $(P_C)_{220} = 10(P_C)_{240}$. From the standard COESA atmosphere, $(P_A)_{220} = 1.6(P_A)_{240}$. Insertion into Eq. (5), along with the appropriate k, leads to $0.16(10\,P_CP_A)/1.7(1.6\,P_AP_C) = 0.6$ in reasonable agreement with the requirement of Eq. (5).

The foregoing discussion appears to be in good agreement with the observations of the glow on spacecraft. Although it has been implied before that agreement should be evident between AE and Shuttle glow in their total brightness and altitude dependence, the results here give, for the first time, validity to the suggestion. The results of the thruster glow analysis show the one-to-one correspondence between the TV pictures and the integrated video signal. It also gives an indication of the possible mechanism of glow production arising from thruster firings.

Also, the results obtained here for the time constants of the gas phase glow and the surface glow for STS-3 are in good agreement with those from individual pixels as determined by R. R. Herm and G. C. Light [Aerospace Corp., Report TOR-0084A (5464-04)-]. In Table 8 there, for pixels viewing just the gas phase the average of eight values is $5.9\ s^{-1}$, and for pixels viewing the surface glow the average of three values is $1.1\ s^{-1}$.

References

[1]Banks, P. M., Williamson, P. R., and Raitt, W. J., "Space Shuttle Glow Observations," *Geophysical Research Letters*, Vol. 10, 1983, p. 118.

[2]Mende, S. B., Garriott, O. K., and Banks, P. M., "Observations of Optical Emissions on STS-4," *Geophysical Research Letters*, Vol. 10, 1983, p. 122.

[3]Yee, J. H. and Abreu, V. J., "Visible Glow Induced by Spacecraft-Environment Interaction," *Geophysical Research Letters*, Vol. 10, 1983, p. 126.

[4]Mende, S. B. and Swenson, G. R., "Vehicle Glow Measurements on the Space Shuttle," AIAA Paper 85-0909, June 1985.

[5]Dalgarno, A., Yee, J. H., and Le Compte, M., "The Atmospheric Explorer and Shuttle Glow," NASA 2391, May 1985.

[6]Swenson, G. R., Mende, S. B., and Clifton, K. S., "STS-9 Shuttle Glow; Ram Angle Effect and Absolute Intensities," *Geophysical Research Letters*, Vol. 13, 1986, p. 509.

[7]Kendall, D. J., Gattinger, R. L., Llewellyn, E. J., McDade, I. C., and Mende, S. B., "Orbiter Glow Observations at High Spectral Resolution," NASA 2391, May 1985.

[8]Kendall, D.J., Llewellyn, E. J., Gattinger, R. L., and Mende, S. B., "Orbiter Glow at High Spectral Resolution," AIAA Paper 85-7000, Nov. 1985.

[9]Yee, J. H. and Dalgarno, A., "Radiative Lifetime Analysis of the Shuttle Optical Glow," AIAA Paper 83-2660, Oct. 1983.

[10]Torr, M. R., "Optical Emissions Induced by Spacecraft-Atmospheric Interactions," *Geophysical Research Letters*, Vol. 10, 1983, p. 114.

[11]Swenson, G. R., Mende, S. B., and Clifton, K. S., "Ram Vehicle Glow Spectrum; Implication of the NO_2 Recombination Continuum," *Geophysical Research Letters*, Vol. 12, 1985, p. 97.

[12]Mende, S. B., Swenson, G. R., Clifton, K. S., Gause, R., Leger, L., and Garriott, O. K., "Space Vehicle Glow Measurements on STS-41-G," *Journal of Spacecraft and Rockets*, Vol. 23, 1986, p. 189.

[13]Anderson, D. N. and Bernhardt, P. A., "Modeling the Effects of an H_2 Gas Release on the Equatorial Ionosphere," *Journal of Geophysical Research*, Vol. 83, 1978, p. 4771.

[14]Glasstone, S., *Textbook of Physical Chemistry*, Van Nostrand, New York, 1946, pp. 1044–1126.

1987 *Journal of Spacecraft and Rockets* Index

How to Use the Index

In the Subject Index, pages 569-572, each technical paper is listed under a maximum of three appropriate headings. Note the number in boldface type following each paper title, and use that number to locate the paper in the Chronological Index. The Author Index, page 572, lists all authors associated with a given technical paper. The locating numbers are identical to those in the Subject Index. The Chronological Index, pages 573-576, lists all papers by their unique code numbers. This listing contains titles, authors and their affiliations, and volume, issue number, and page where the paper appeared. It also gives the AIAA paper number, if any, on which the article was based, as well as the "CP" or conference volume number if the paper was published in a bound collection of meetings papers. Comments, Replies, and Errata are listed directly beneath the paper to which they refer. If the paper to which they refer was published prior to 1987, that paper also will appear in both the Subject and Chronological Indexes. Authors of Comments also are listed in the Author Index.