Space Vehicle Glow and Its Impact on Spacecraft Systems

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Introduction

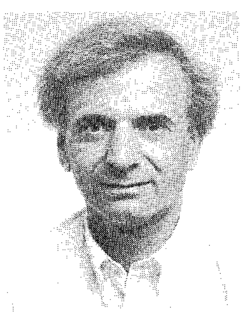
Background

As more and more complex systems are flown in space, environmental effects on space systems that were once overlooked, or considered second-order effects, have become serious concerns for the spacecraft designer. Single event upsets, oxygen erosion, and the subject of this review, space vehicle glow, all represent such interactions. Although suspected on several early rocket flights (e.g., by Heppner and Meredith[1] and others), vehicle glow went essentially undetected until the late 1970's. As reported in numerous recent papers (see Refs. 2–4 and references therein), glow, as it may potentially have an impact on measurements in the IR, UV, and visible spectral bands of importance to many optical sensor systems, threatens to be a particularly serious contamination issue. The likelihood for observing limitations on optical systems such as the Space Telescope and numerous DoD sensor systems could seriously impact the design and operation of these systems. Fortunately, with adequate understanding of the processes involved, it should be possible to design these systems so that the worst aspects of the phenomenon can be limited in their impact on operations. The purpose of this review, therefore, is to provide a characterization of space vehicle glow so that means for limiting its impact on spacecraft systems can be developed.

Environment

Before reviewing the characteristics of space vehicle glow, the environment in which glow takes place will be briefly described.

Dr. Henry B. Garrett completed his undergraduate (Physics, 1970; Magna cum Laude and Phi Beta Kappa) and graduate education at Rice University (M.S., 1972; Ph.D., 1973 space physics and astronomy). He joined the Air Force Geophysics Laboratory in 1974 where he served for six years and received the Air Force's Harold Brown Award for his work in spacecraft charging and environmental modeling. Dr. Garrett, on completion of his military obligation, joined the staff of the California Institute of Technology's Jet Propulsion Laboratory where, since 1980, he has served as a member of the technical staff, as a group supervisor, and as Division Technologist in the Reliability Engineering Section. He is a member of the American Geophysical Union, the American Physical Society, the Astronomical Society of America, Sigma Xi and AIAA, and has written numerous papers in space physics and aeronomy. His AIAA activities include serving on various AIAA committees and editing the AIAA book *Space Systems and their Interactions with the Earth's Space Environment.* He is currently Associate Editor of the *Journal of Spacecraft and Rockets.*



Dr. Ara Chutjian received his Ph.D. from The University of California, Berkeley, in 1966. After a postdoctoral stay at AT&T Bell Laboratories and the University of Southern California, he joined the Jet Propulsion Laboratory in 1969, where he is currently a team leader in the Atmospheric and Cometary Sciences Section. Dr. Chutjian and his group carry out research in several areas of atomic and molecular physics. These include electron-ion scattering by energy-loss methods, molecular attachment at ultralow electron energies, and the generation of fast oxygen atoms for the study of the Shuttle "glow" phenomenon.

Dr. Stephen B. Gabriel received his B.Sc. (1971) and Ph.D. (1974) from Strathclyde University, Glasgow, Scotland, U.K., for his laboratory studies of plasma. He subsequently did post-doctoral work (1975–1979) at the University of Bristol, England, U.K., in ion thrusters. From 1979 to 1983, he served as a member of the technical staff in the Electric Propulsion and Plasma Technology Group at the California Institute of Technology's Jet Propulsion Laboratory. There he carried out research in magnetoplasmadynamic thrusters, spacecraft-plasma interactions, biomedical applications of ion thruster technology, and magnetoplasmadynamic thurster erosion effects. Dr. Gabriel then took up a position as Senior Systems Engineer for the British Aerospace Dynamics Group from 1983 to 1985. He returned to the Jet Propulsion Laboratory as Group Supervisor for the Natural Space Environments Group, Reliability Engineering Section, in 1985, where he is currently employed. He is a member of the AIAA and IEEE and has published a variety of papers on space plasma and their interactions with space systems.

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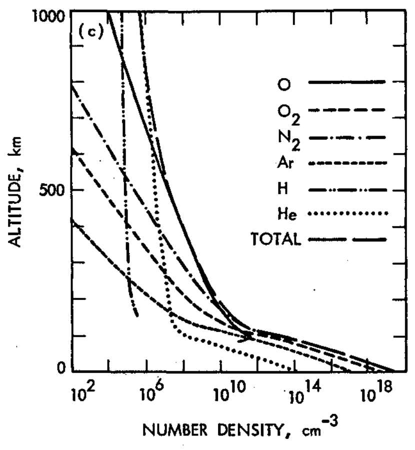


Fig. 1a Neutral atmosphere profiles for average geophysical conditions on the day side.[5]

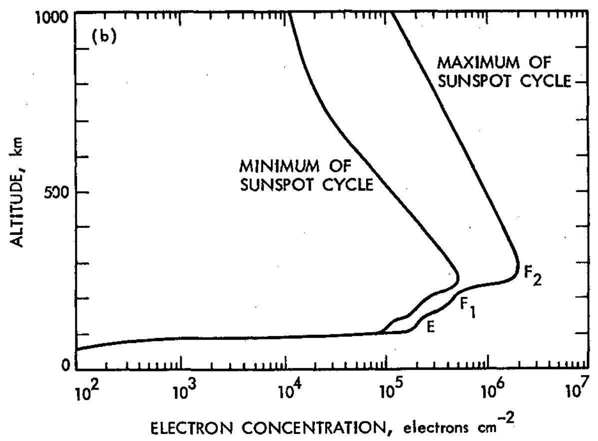


Fig. 1b Midlatitude daytime ionospheric profiles for sunspot minimum and maximum conditions.[5]

In Fig. 1,[5] the variations of the neutral atmosphere and the ionosphere at orbital altitudes between about 100 and 1000 km are plotted. This is the region in which vehicle glow has been observed. For purposes of this review and for most practical applications, the neutral atmosphere (see Fig. 1) will be considered to consist mainly of atomic oxygen (note: atomic hydrogen can dominate occasionally above 500 km for low exospheric temperatures) with traces of molecular oxygen, molecular nitrogen, and atomic hydrogen over the altitude range of interest. Helium, nitric oxide, atomic nitrogen, and argon are also present below the 1% level. (For general descriptions of the upper atmosphere, see Refs. 6 and 7 and references therein; widely used neutral atmosphere models are those in Refs. 8–10.) The thermal temperature of the constituents varies approximately exponentially from ~ 100 K at 100 km to 500–1500 K at 1000 km, depending on solar cycle, latitude, and local time, with excursions to 2000 K during high levels of geomagnetic activity. As spacecraft between 100 and 1000 km are moving at about 7.8 km/s, the resulting impact energy of the particles can reach values on the forward (or ram) surface of the spacecraft well in excess of 5 eV (varying from 4.6 eV for N to 10.25 eV for O_2). These ram energies are sufficiently high to induce chemical reactions, including oxygen erosion. Furthermore, the large ratio of directed velocity to thermal velocity means that pronounced anisotropies exist in the flux to the vehicle. This has led to gross asymmetries in the glow phenomenon, with surface glow appearing primarily on surfaces that face into the vehicle velocity vector. A final issue when considering the influence of neutral environment on glow is the chemical composition of the particles striking the spacecraft surfaces. The fact that atomic oxygen typically dominates, for example, places limits on the proposed theories for glow.

Also illustrated in Fig. 1 is the second environment of potential importance to the study of glow, the ionosphere. On the sunlit hemisphere of the Earth, X-rays, EUV, and UV radiation penetrate the neutral atmosphere, ionizing and exciting the molecules present. As the radiation penetrates, there is a balance between increasing neutral density and increasing absorption that leads to the formation of layers (principally the *F* layer between 150 and 1000 km, the *E* layer between 100 and 150 km, and the *D* layer between 60 and 100 km) that gives rise to the mean structure called the ionosphere. (For general descriptions of the upper ionosphere, see Refs. 6 and 7 and references therein; a widely used ionospheric model is Ref. 11.) These layers are the combined result of the absorption/increasing density process and complex chemical reactions within the atmosphere and ionosphere. The local-time peak in the ionospheric density parallels that of the neutral density bulge, occurring approximately 2 h after local noon. The ionospheric composition likewise follows that of the neutral atmosphere, varying roughly from NO^+/O_2^+-dominated in the *D* region, to O^+-dominated in the *E* region, to H^+-dominated in the *F* region (chemical reactions complicate the picture). Densities reach 10^6 cm^{-3} at the peak in the *F* region at about 300 km on the sunlit side. At night, the peak ion density can fall below 10^5 cm^{-3}, and the composition can change from O^+ to H^+ above 500 km. Temperatures follow roughly that of the neutral atmosphere, increasing exponentially from a few hundred K at 50–60 km to 2000–3000 K above 500 km (i.e., a few tenths of an eV). The electron temperature tends to be a factor of two greater than that of the neutrals, with the ion temperature falling in between.

The induced contaminant environment is also an important consideration in studying the glow associated with the Shuttle. As will be discussed later, satellites typically are on orbit long enough to lose most of their contamination cloud. In situ measurements indicate that the pressure in the vicinity of the Shuttle varies from ambient levels of 10^{-7} Torr to enhanced pressures in the ram direction or during thruster firings of 10^{-4} Torr. These enhanced levels imply that the mean free path between collisions is often less than Shuttle dimensions, so that particles from local contamination sources can be scattered back onto the Shuttle. The induced environment around the Shuttle will therefore be dominated by local variations, making any straightforward identification of the consituents involved in the glow process difficult.[2] In this environment, H_2O and CO_2 are the dominant species,[12-14] with traces of He, O_2, Ar, freon, cleaning agents, etc., present.

Observations

Introduction

Glow observations have been assumed to fall into two categories, dependent apparently on the size of the perturbing object: those associated with normal-sized (small) spacecraft (AE-C, AE-E, and DE-B satellites) and those associated with the (large) Space Shuttle. It is believed that, based on the differences in the observed glows, there may be different or perhaps geometry-dependent processes in operation. The relevant glow observations have been made primarily by three types of instruments: ground-based telescope systems,[15] onboard spectrometer measurements (typically incidental to the primary measurements), and hand-held photographic instruments looking out the cabin windows of the Shuttle. Unfortunately, none of the measurement techniques has been able to uniquely determine the characteristics of the glow and, indeed, they sometimes present conflicting data. It is likely that, in addition to glows associated with satellites and the Shuttle, there may be a further division of the Shuttle glow into surface or ram glow (a brightness observed when looking along Shuttle surfaces exposed to the ramming atmosphere), thruster-induced or gas-phase glow (a significant brightness observed immediately following thruster firings) and, for want of a better word, cloud glow (the latter observed when looking perpendicular to and away from, rather than along, Shuttle surfaces). Further divi-

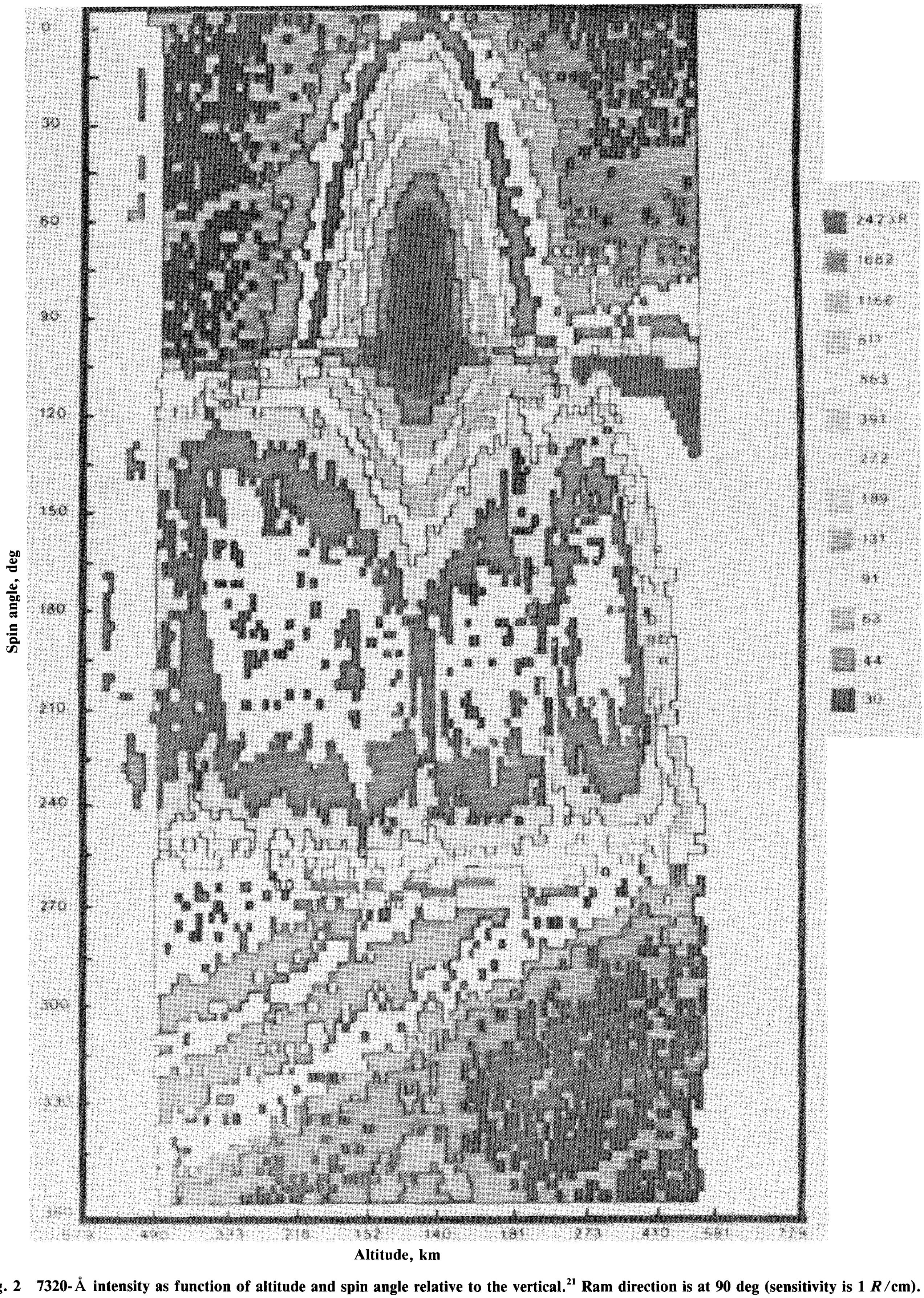


Fig. 2 7320-Å intensity as function of altitude and spin angle relative to the vertical.[21] Ram direction is at 90 deg (sensitivity is 1 R/cm).

sions are also possible. This section will present observations of each of these glows in order to identify key parameters and common features, thereby allowing the development of mitigation techniques based on the "symptoms."

Satellites

As mentioned, there are apparent differences between observations made on satellites and on the Shuttle. As noted by Green,[2] this is not too surprising in that the on-orbit environment associated with satellites should be much cleaner than that of the Shuttle: Satellites are in orbit for years, so outgassing has time to decrease (although Atmospheric Explorer data indicated that the observed glow may be actually increasing with time as surfaces age[16]); there are fewer thruster firings; and, perhaps more importantly, there are typically no significant local sources of H_2O or CO_2 such as the Shuttle life support systems. It also should be noted that satellite thruster systems typically point away from spacecraft surfaces, whereas the Shuttle's thrusters often point toward spacecraft surfaces. This apparently allows trapping of the Shuttle thruster products for a sufficiently long time that a glow is generated (as discussed later).

The satellite observations to be reported here are from the AE-C, AE-E, and DE-B satellites, with some UV measurements from the Air Force STP 78-1 and S3-4 spacecraft. In this section, these observations will be discussed only briefly since measurements were generally incidental to the intended purpose of the instruments and as a consequence were not optimized for glow studies. Indeed, the glow detected can be considered as an example of optical contamination. However, the long duration and unconstrained nature of satellite observations make them of value in evaluating long-term spatial and temporal variations in the glow caused by the ambient environment. In contrast, the Shuttle observations to be discussed later, particularly those of Mende and his co-workers, were often specifically planned to study glow.

NASA AE-C and AE-E Satellites

The earliest published observation clearly identifying the so-called vehicle glow is that of the Atmospheric Explorer C satellite (AE-C). This phenomenon is illustrated in Fig. 2, where the glow intensity at 7320 Å is plotted as a function of the satellite altitude and its spin angle relative to the vertical. (The ram or velocity vector direction is at 90 deg.) The pronounced enhancement in the ram direction below 500 km is the vehicle glow. This type of vehicle glow has been detected on both the AE-C and AE-E satellites.[17] On the AE-E and the highly eccentric AE-C satellite, the principal instrument of value in studying glow was the Visual Airglow Experiment (VAE).[18] This instrument was intended to observe atomic and molecular features in the terrestrial airglow layer between 2800 and 7320 Å.[17] In the process of making these observations, the photometer filter channel backgrounds were found to have a variability with ram angle,[17-21] as illustrated in Fig. 2. The data indicated detectable levels of luminosity in the instruments' near-UV channels (3371 Å) with increasing luminosity toward red wavelengths (7320 Å) at altitudes up to 450 km (Fig. 3). Analysis of these data suggested that the glow extended well away from the satellite (the scale length was 1–10 m above the 75-cm AE satellite).[16] This was interpreted as implying long-lived, metastable emitters.

Of particular importance in understanding the source of vehicle glow. Yee and Abreu[20] found a strong correlation between ram emission intensity and altitude (Fig. 4). The brightness closely followed the atomic oxygen scale height above 160-km altitude, so that it was proportional to $[O]$ (brackets will be used to signify density). Below about 140–180 km, the brightness scaled quadratically with neutral molecular density, $[N_2]^2$ (Ref. 16) or linearly with $[O_2]$ (Ref. 22). As a result, atomic oxygen was proposed as a probable chemical catalyst for whatever process was occurring.[22] The OH Meinel bands were suggested as a likely candidate (see Ref. 22 for the OH hypothesis). Yee and Abreu[20] determined the angular distribution of the brightness to vary as $\cos^3(\phi)$, with respect to the angle of attack ϕ (Fig. 5), implying that the brightness is proportional to flux × impact energy; i.e., incident particle flux is proportional to $v\cos(\phi)$, whereas the impact energy is proportional to $[v\cdot\cos(\phi)]^2$, where v is the spacecraft velocity.[20]

NASA DE-B Satellite

The glow phenomenon was not limited to the AE satellites, but was subsequently reported for the NASA Dynamics Explorer B satellite (DE-B or DE-2). A high-resolution Fabry-Perot interferometer (FPI) was carried on DE-B.[23] This consisted of a filter centered on 7320 Å (± 10 Å) in series with a Fabry-Perot etalon.[24,25] Abreu et al.[25] have suggested that the ram glow spectrum observed was similar to the OH ($X^2\Pi$) spectrum of nightglow from the atmospheric limb. Langhoff et al.[26] subsequently made extensive comparisons of the spectrum with the OH emission spectrum that support this suggestion.

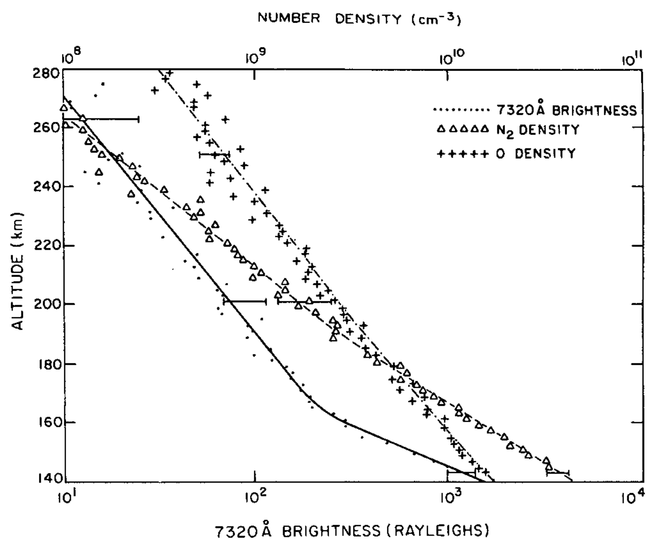


Fig. 4 7320-Å ram glow intensity (dots) in Rayleighs as a function of altitude from the AE satellites.[18] N_2 (open triangles) and O (plus symbols) densities are in cm^{-3}.

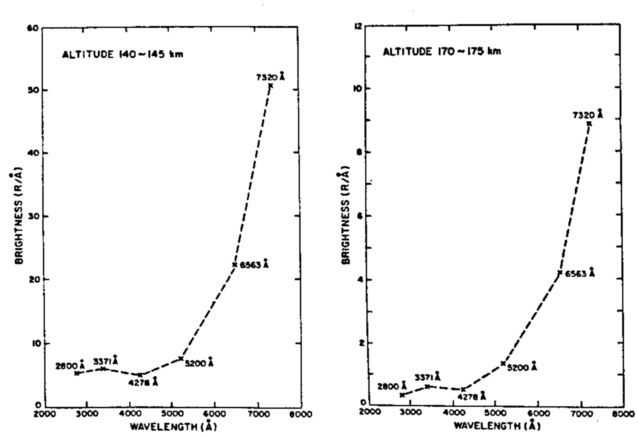


Fig. 3 The spectral variation of the glow as measured on the AE satellites at a) 140–145 km, and b) 170–175 km.[18]

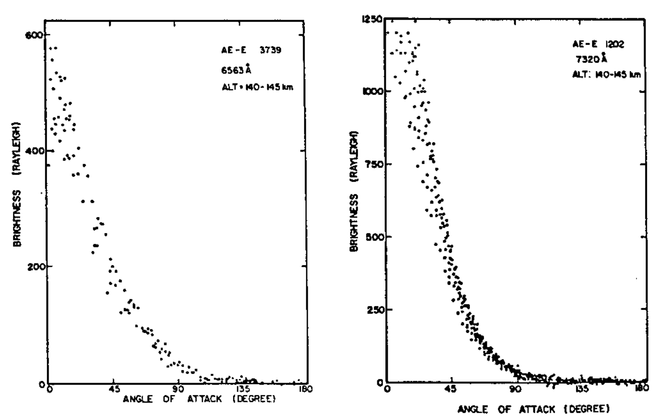
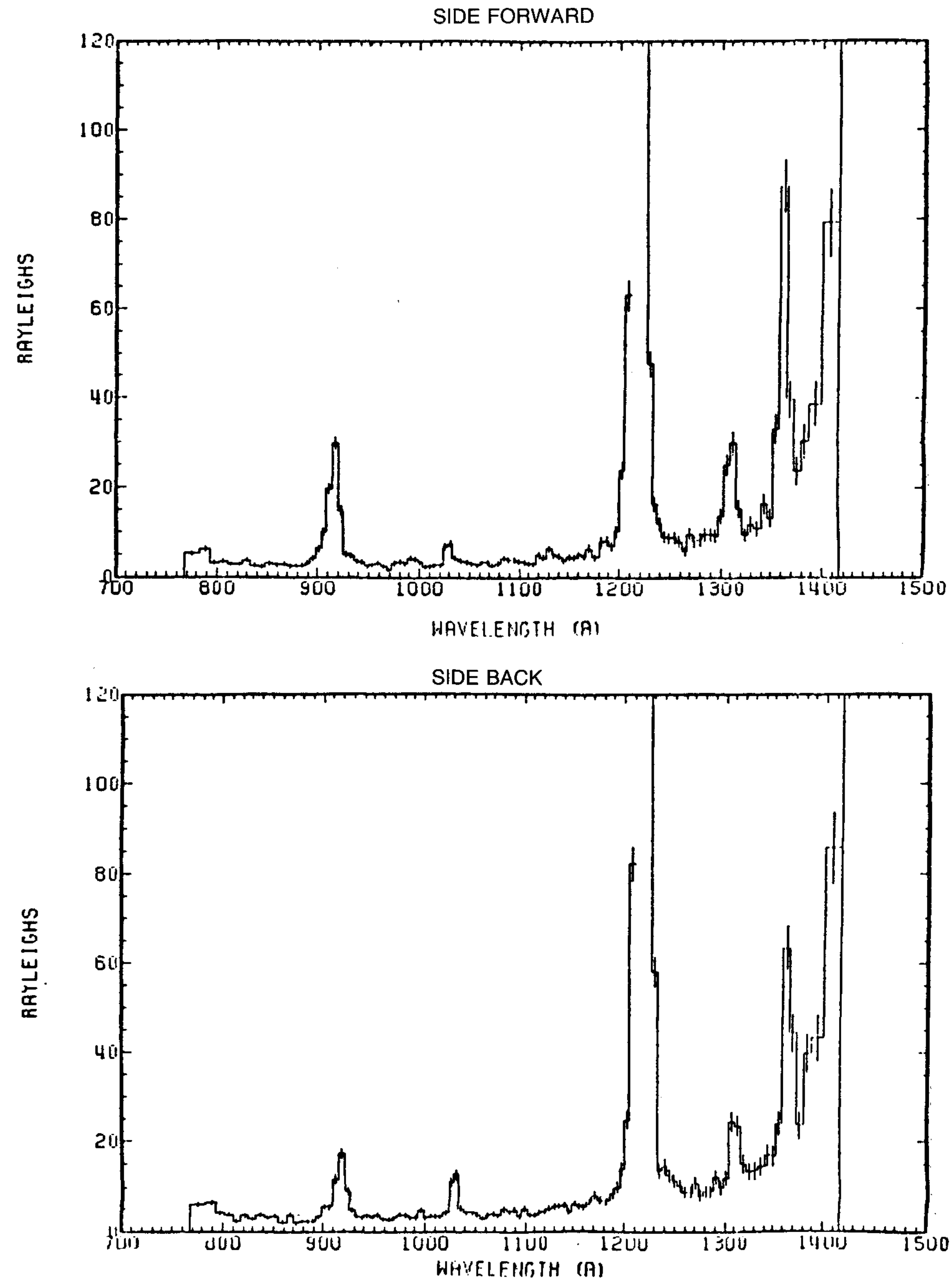


Fig. 5 Angular dependence of glow brightness at a) 6563 Å, and b) between 140–145 km.[18]



a) Forward-looking direction

b) Backward-looking direction

Fig. 6 UV spectra obtained by Chakabarti and Sasseen[27] from the AF STP 78-1.

AF STP 78-1 and S3-4 Satellites

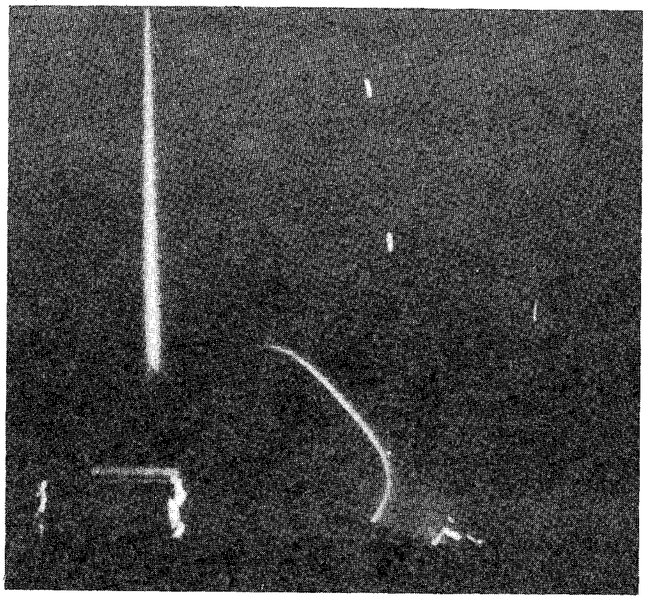
Recently, Chakrabarti and Sasseen[27] have observed hydrogen Lyman-alpha (1216 Å) emission on the U.S. Air Force Space Test Program (AF STP) 78-1 satellite[28] at 600 km from March 21–28, 1979. They interpreted the observed Lyman-alpha modulation with ram angle to be caused by an excess glow of several hundred R (R = Rayleigh = 10^6 photons/cm^2-s) intensity above the interplanetary Lyman-alpha background. Some of their results are plotted in Fig. 6. The case for UV glow is unclear, however. Bixler et al.[29] have also observed a glow in the UV between 1300 and 1800 Å on STS-9/SL-1, but Huffman et al.[30] did not see any glow on STS-4 between 1100 and 1800 Å. Given the great variability of the atmosphere and the differences in the Shuttle and satellite environments, these differences may not be surprising.

Recent analysis of the N_2 Lyman-Birge-Hopfield (LBH) bands on the satellite S3-4 shows a strong dependence of the LBH nightglow with altitude.[31] The viewing directions were toward the nadir rather than directly at a surface. The total integrated LBH intensity between 1400 and 1700 Å was found to have an altitude dependence of $[N_2]^2[O]$ or $[N_2]^3$ between about 180 and 220 km.

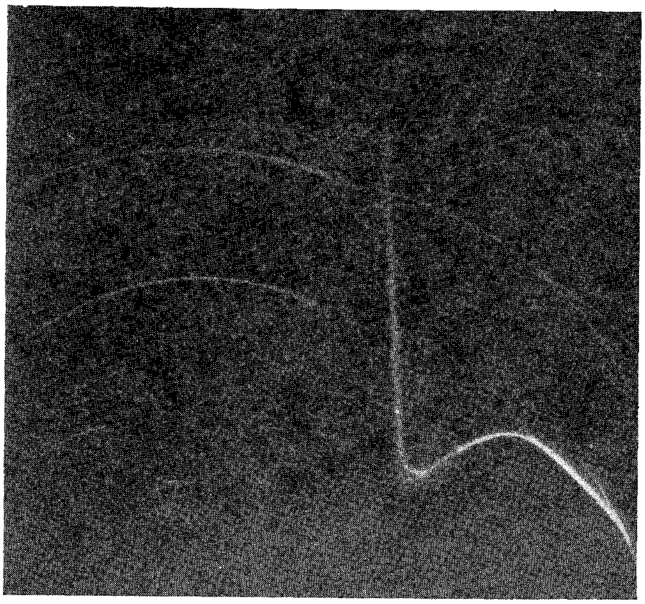
Shuttle Observations

Shuttle Ram Glow

The first reported glow observations on the Shuttle were reported on STS-3 by Banks et al.[32] (Fig. 7a). Glow observations subsequently have been reported by investigators from Shuttle missions STS-3, STS-4, STS-5, STS-8, STS-9, 41-D, 41-G, 51-D and 61-C.[32–50] The observations of glow reported in Ref. 32 were from the Orbiter television camera and from still-camera pictures of the aft Shuttle surfaces. These showed that the glow, as observed previously on the AE satellites, was only on surfaces facing into the velocity vector. This effect, from a later STS mission,[44] is clearly illustrated in Fig. 8. A glow emission associated with the operation of the STS-3 electron accelerator experiment was also noted by Banks et al.[32]



a) STS-3 at 240 km,[32] and 10 s exposure



b) STS-5 at 305 km and 100 s exposure[44]

Fig. 7 STS-3 photgraph through aft flight deck window of tail and port engine pod. STS velocity vector is from upper right.

Observations by Yee and Dalgarno[51] on STS-3 are also typical of the Shuttle-related glow. They reported an intensity along the line of sight for the glow of about 30 kR on STS-3 that, from their theoretical calculations, corresponded to a maximum volume emission rate of 7×10^6 photons/cm^3-s. The glow intensity decreased exponentially with distance from the surface, with a scale length ($1/e$ distance) of 20 cm for an isotropic flux (~ 14 cm normal to the surface). If it is assumed that the emitting molecules are in thermal equilibrium with the Shuttle surface, then their mean speed is 0.3 km/s. This gives a lifetime of 0.67 ms for the emitting species.

The most extensive observations of Shuttle-related glow have been reported by Mende and co-workers on STS-3, -4, -5, -8, and -9 (see Refs. 3, 33, 34, 37, 38, 44, 46, and 52). Their experiments, consisting of photography out the rear bay windows, have been of great value in obtaining an initial understanding of glow. For example, on STS-4, a transmission grat-

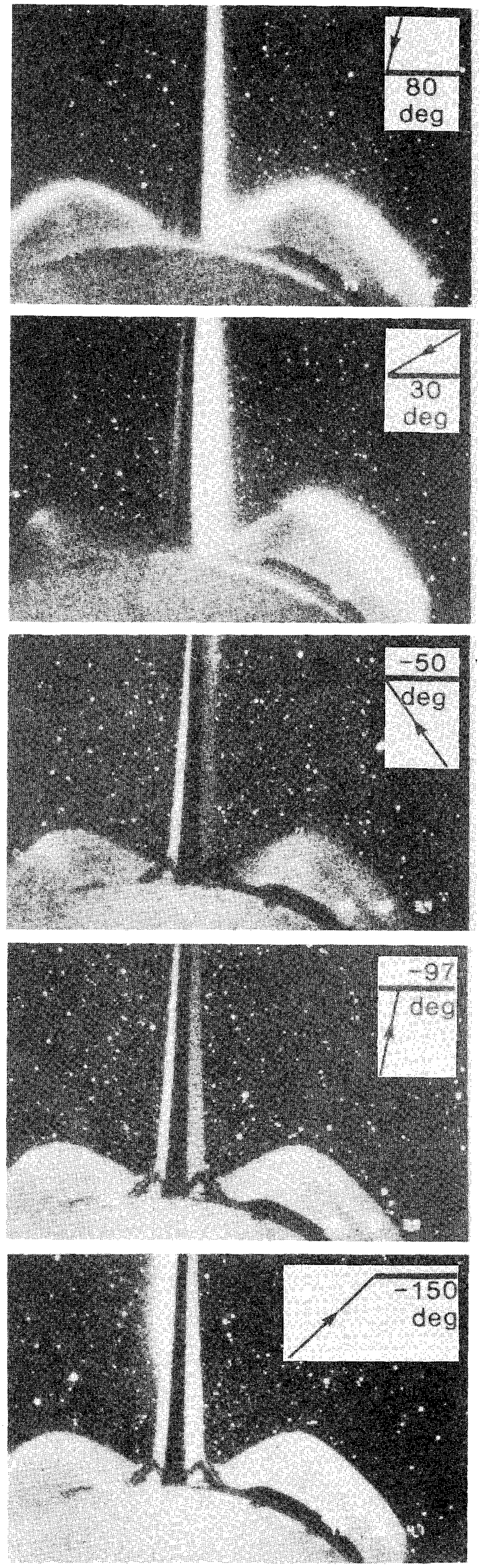


Fig. 8 Variations of Shuttle ram glow as a function of ram direction (arrows indicate direction of velocity vector) for STS-5.[44]

ing was placed in front of a photographic camera[33] to obtain a coarse spectrum. On STS-5 and later flights an image intensifier was used with the camera to obtain both coarse spectral resolution data and photographic data. On STS-4, -5, -8, and -9, this objective grating image clearly demonstrated the existence of a red structureless glow extending away from the vertical stabilizer.[37,38,44] Typically, a spectral resolution on the order of 150 Å was obtained by these surveys. An objective grating glow spectrum, obtained on STS-8 in September 1983,[44] is illustrated in Fig. 9. This photograph demonstrates that the spectrum has little glow between 4300 and 5000 Å and increases above 5000 Å. (The instrument resolution was 31 Å FWHM.) Mende and his colleagues successfully separated this spectrum from light reflected off the Shuttle and resolved airglow atomic emissions, OH band emissions, and a very strong atmospheric O_2 band emission at 7620 Å. The spectra show that any OH emission, if present in the Shuttle glow, is immersed in a continuum spectrum.

On 41-D,[44] the optical detection experiment was significantly upgraded. A special glow spectrometer with the following three modes of operation was flown: 1) image intensifier mode, 2) grating-produced objective spectrum – slitless spectrum mode, and 3) high-resolution spectrographic mode (34 Å resolution) with a slit to exclude contamination from scattered airglow.

Results from the flow spectrometer on 41-D are presented in Fig. 10. Again, the spectrum peaks near 6800 Å, as implied by the STS-8 spectrum already discussed.[44] No distinct spectral features, such as molecular band spectra, were observed, indicating a continuum at the 34-Å resolution limit of the 41-D instrument.

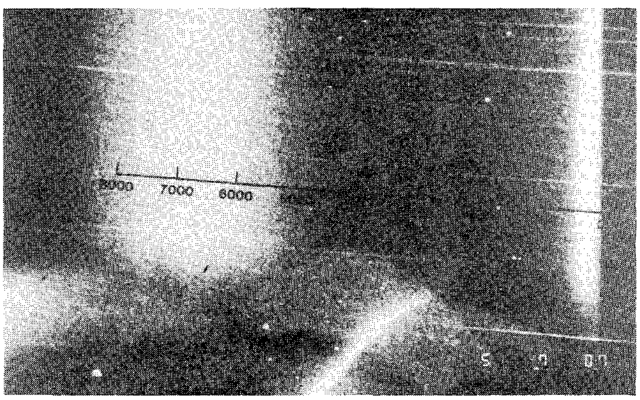


Fig. 9 STS-8 objective spectrum photograph of ram surface glow.[44] Wavelength scale is superimposed on the picture.

On STS-5, the Orbiter was rotated around the x axis (taken as the nose-to-tail axis). Results demonstrated that the glow occurred over a large angle, for as the angle relative to the velocity vector decreased, the glow grew more intense. Interestingly, Mende and Swenson[44] found that the STS-3 (240 km) glow was 3.5 times brighter than STS-5 (305 km) when exposure time and film reciprocity were considered (Figs. 7a and 7b). This height variation is consistent with the findings of Yee and Abreu[18] (see Fig. 4). The intensity was not strictly proportional to the cosine of the angle, however, as cos (ϕ) decreased faster than the observations. The glow was therefore not strictly proportional to the flux of incoming atmospheric consituents. They suggested that this might be because incoming particles at large ram angles are more likely to produce glow than particles at normal incidence. Their later work on STS-9 indicates that it may also be caused in part by the thermal velocity of the particles perpendicular to the flow velocity and to reflected particles from other surfaces.[47] In the latter case, however, Slanger,[53] in reviewing photographic data from STS-5 as a function of ram angle, found that the glow was most likely the result of the direct interaction of fast particles with tile surfaces. Green[2] suggests another possible explanation by noting that the Shuttle tile surfaces are very structured, so that there is almost always a surface facet normal to the velocity vector, even at large angles of attack.

As discussed earlier, Yee and Dalgarno[51] found a scale length ($1/e$ folding length) of 20 cm from the Shuttle surface for the glow. If it is assumed that this is the result of excited particles leaving with a fixed velocity (unknown), this scale length is characteristic of the lifetime of the emitting species (distance = departure velocity × lifetime). In agreement with these findings, after geometric corrections, the data from Mende et al.[38] on STS-9/Spacelab 1 similarly showed an exponential decay of the glow with a scale length of 20 cm. A plot of this behavior is shown in Fig. 11. The phenomenon may be temperature, size, or geometry dependent, however, as they also reported that the scale length was only 6 cm above the Remote Manipulator System (RMS).

In addition to the aforementioned influences on the Shuttle surface glow, Mende and Swenson[44] have observed variations in glow intensity with surface material. On STS-8 (220 km), the Shuttle crew photographed the glow above 4-in.-wide tape samples attached to the RMS.[3,44] These were ordered as kapton, aluminum, black chemglaze (Z306), aluminum, and kapton. The kapton was selected because it is known to be sensitive to oxygen erosion; aluminum was selected because of its resistance

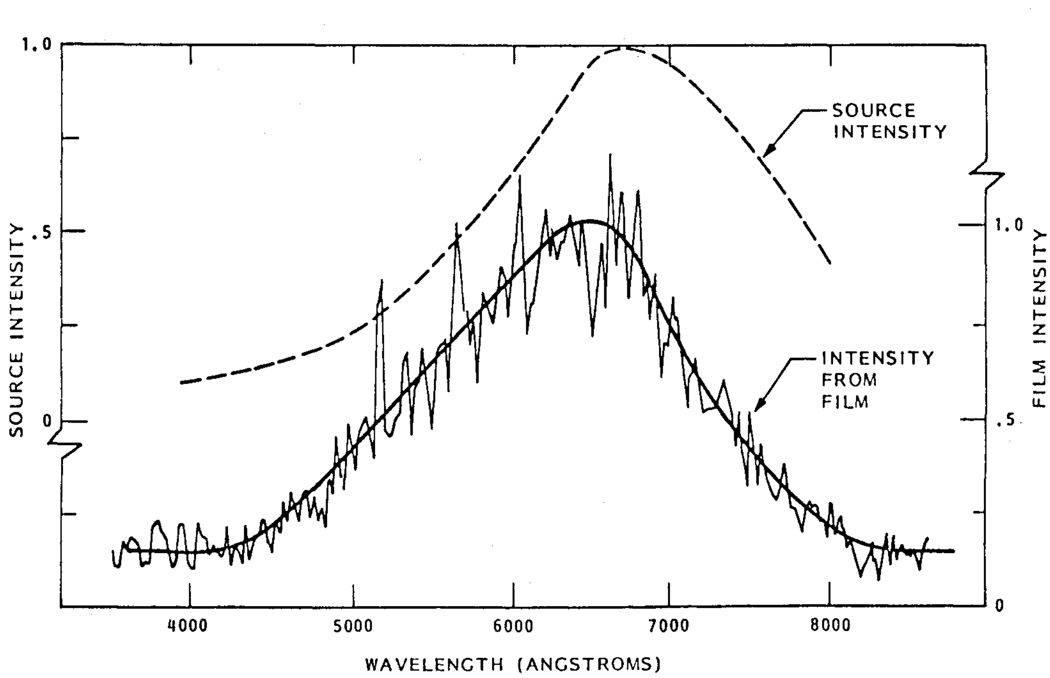


Fig. 10 Bottom plot is of film intensity from a ram glow spectrum measured on STS 41-D corrected for the D-log-E response of the film. Top plot is of the spectrum corrected for the instrument response.[44]

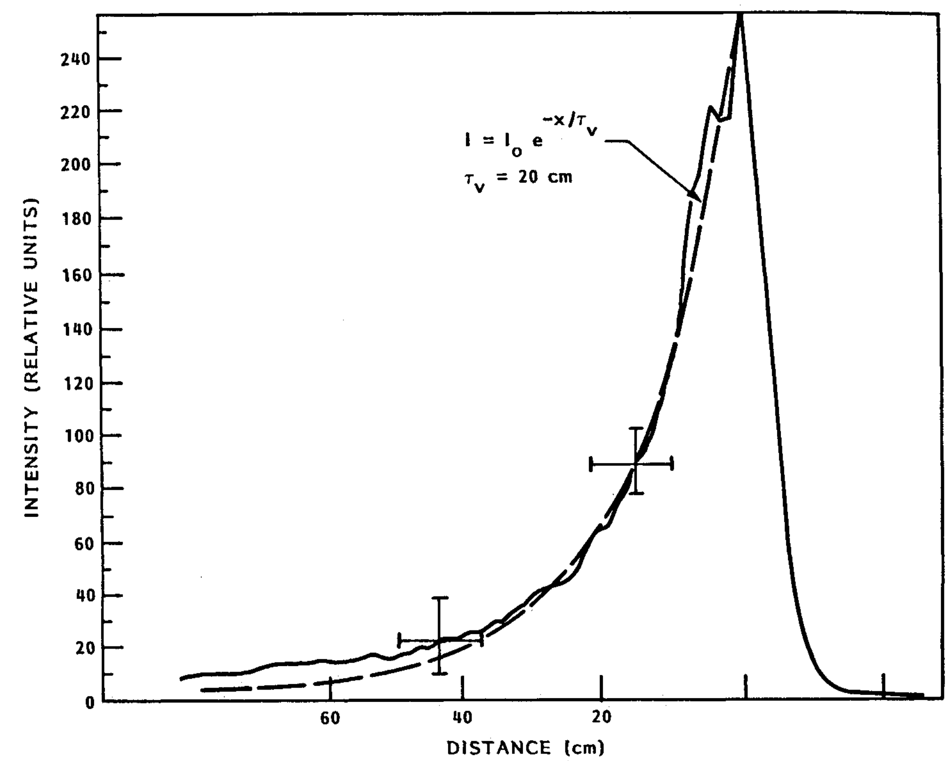


Fig. 11 Ram glow intensity as a function of distance from the Shuttle tail surface for STS-9.[44] Also shown is an exponential fit with a scale length of 20 cm.

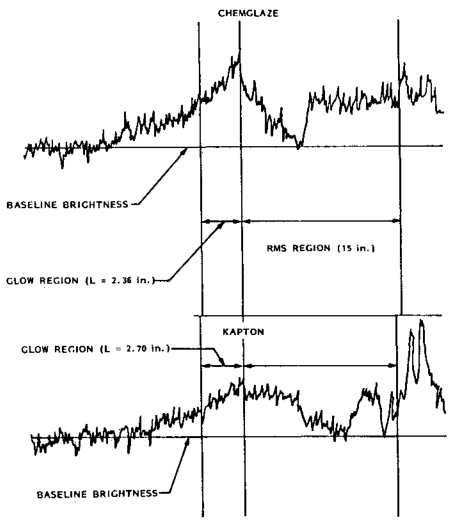


Fig. 12 Ram glow intensity as a function of distance over chemglaze and kapton samples on the RMS (from STS-8).[44]

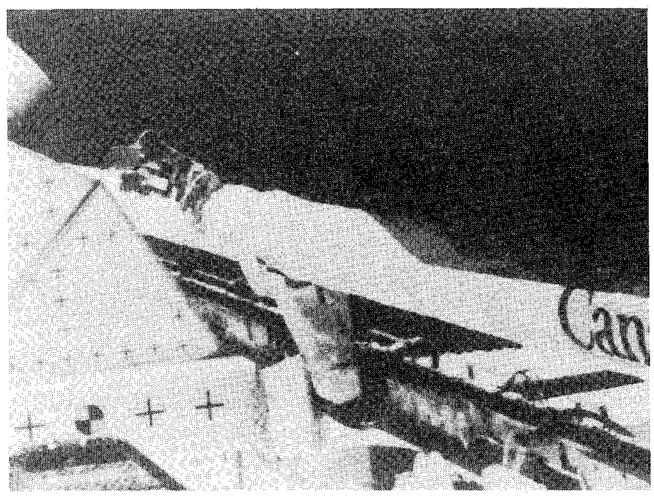


Fig. 13a Photograph (prior to flight) of the STS-8 RMS showing placement of the material samples used to study ram glow variations with composition.[44]

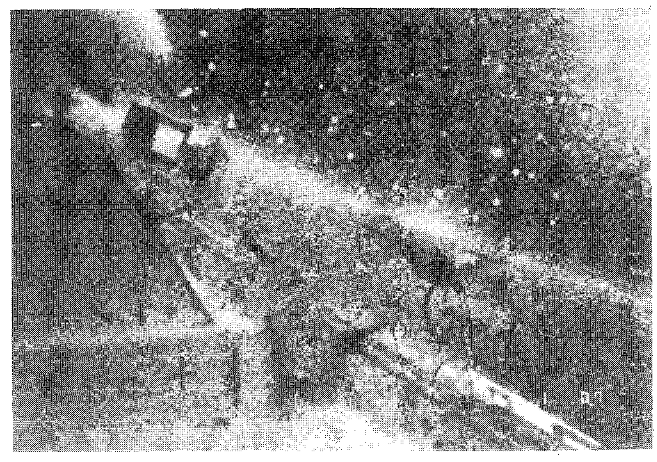


Fig. 13b Same as Fig. 13a, but in darkness showing the variations in surface glow as a function of material.[44]

to erosion. Black chemglaze, a carbon-filled, polyurethane-based, matte black absorbing paint, was studied because it is used in low-light level detection devices. Mende and Swenson observed that, whereas the intensity of glow was different between samples, the scale length was similar. Typical data illustrating this behavior are presented in Fig. 12 for chemglaze and kapton. They interpreted this as implying that the lifetimes of the emitting species above each surface were the same. This in turn could imply a common mechanism for the glow independent of sample material. It was determined that chemglaze had the most intense glow and aluminum the least. Photographs of the samples in sunlight and in darkness (illustrating the glow) are presented in Fig. 13. The experiment was repeated on 41-D,[44] where nine samples were flown at an altitude of 300 km. The in situ measurements, like those of Fig. 12, are presented in Fig. 14. In order of sample having the brightest glow to the one having the dimmest, the results were: Z302 (overcoated with Si), MgF_2, Z302, Z306, chemical conversion film, carbon cloth, anodized Al, 401-C10, and polyethylene. Although the high orbit of the 41-D made the intensity of the glow low and hence the

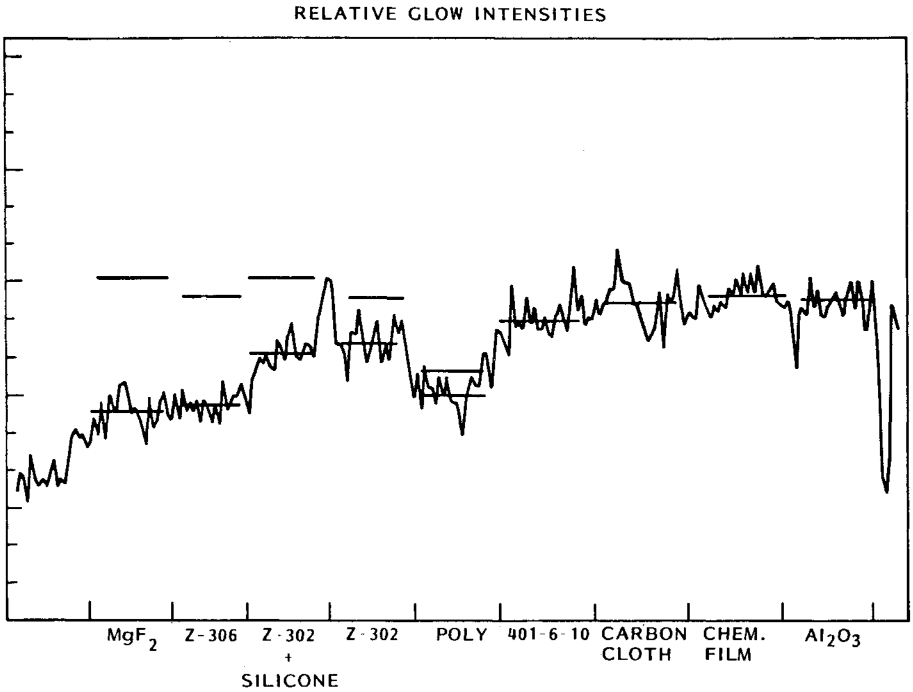


Fig. 14 Uncorrected microdensitometer tracings of nine glow samples of STS 41-D. Also shown are night sky levels above the samples (upper lines) and averages (lower lines).[44]

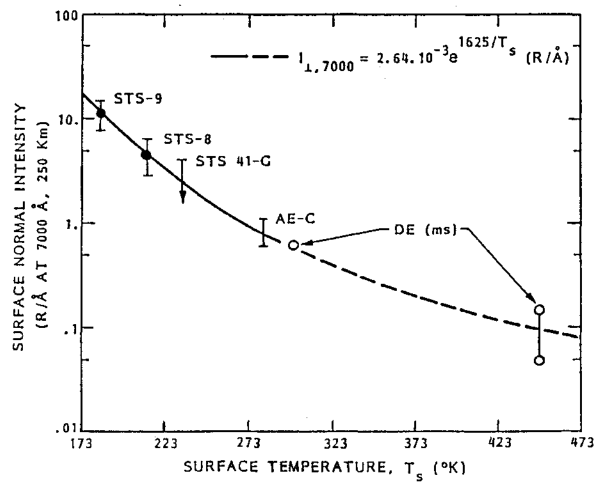


Fig. 15 Ram glow intensity at 7000 Å normalized to 250 km as a function of surface temperature for several satellites and STS missions. An exponential fit to the data in terms of $\exp(E_0/kT_s)$ is also shown. Units are $R/Å$.[48]

data marginal, the results show an order-of-magnitude variation in the samples.

Mende and Swenson have interpreted their results in terms of a glow caused by metastable molecules excited on the surface. Their materials data rule out adsorbed surface molecules present as contaminants, since the glow would then be a function of exposure time and temperature (see below, however). This was not observed: the nearby surfaces were similarly contaminated, yet the glow was different on the different surfaces. Their findings further show that the bulk surface material is not the source of the glowing molecules. If it were, kapton (which erodes the fastest) would glow more than the chemglaze.[44] They interpret the results as indicating that the surface accommodation properties of the samples are important, while the chemical stability of the bulk material is not. The surface acts as a catalyst with the source being the environment (see also Ref. 53).

A final observation associated with the Shuttle surface glow may well be the most crucial. In recently reported results, Swenson et al.[48] found a strong correlation between surface glow intensity and the surface temperature. The clue to this discovery was that on the STS 41-G (a low-altitude mission) glow intensities were much less than measured previously. On 41-G, Kendall et al.[54] (see also Refs. 49 and 55) incorporated a high-resolution (4 Å) Fabry-Perot interferometer used over filter-selected spectral regions. They also employed a camera and image intensifier to take pictures of the Shuttle surface glow in a similar fashion to that of Mende and his colleagues. An $R/Å$ table from their work is presented in Table 1. The 41-G glow intensities are clearly much lower than those of STS-8. The lack of a significant glow on 41-G led Kendall et al.[49] to suggest that the surface temperature might have affected their results by reducing the glow on 41-G relative to other missions. Further study revealed that the surfaces on 41-G were indeed much warmer than for previous missions. When temperature information from the STS missions became available, Swenson et al.[48] found that glow data from the STS-8, STS-9, STS41-G, and, surprisingly, the AE-C and DE-B satellites (note: the AE-C and DE-B points are estimated values) could be fit by a single function $I = 2.64 \times 10^{-3} \exp(1625/T_s)$, where T_s is the surface temperature and I is in $R/Å$ at 7000 Å and 250 km. This behavior is illustrated in Fig. 15. Likewise, they found that variations in material samples could be explained by temperature rather than by other surface variations. If correct, this finding goes far toward explaining the material variations and reconciling differences between satellite glow and Shuttle surface ram glow. It also is consistent with the NO_2 recombination theory (see below) and can be used to determine the surface bond energy of NO (0.14 eV).

Table 1 Brightness of the glow as measured on STS-8 and STS 41-G (after Bareiss et al.[89] from Mende[36] and Kendall et al.[49])

	Brightness (R/Å)		
	STS-8	STS 41-G	
Wavelength (Å)	222 km	230 km	360 km
5577	150	<50	<20
6300	300	90	<35
7300	400	<140	<60
7600	500	<160	<70

ISO — The Cloud Glow

The highest resolution spectra currently available (3 to 6 Å) for vehicle glows were taken by the Imaging Spectrometer

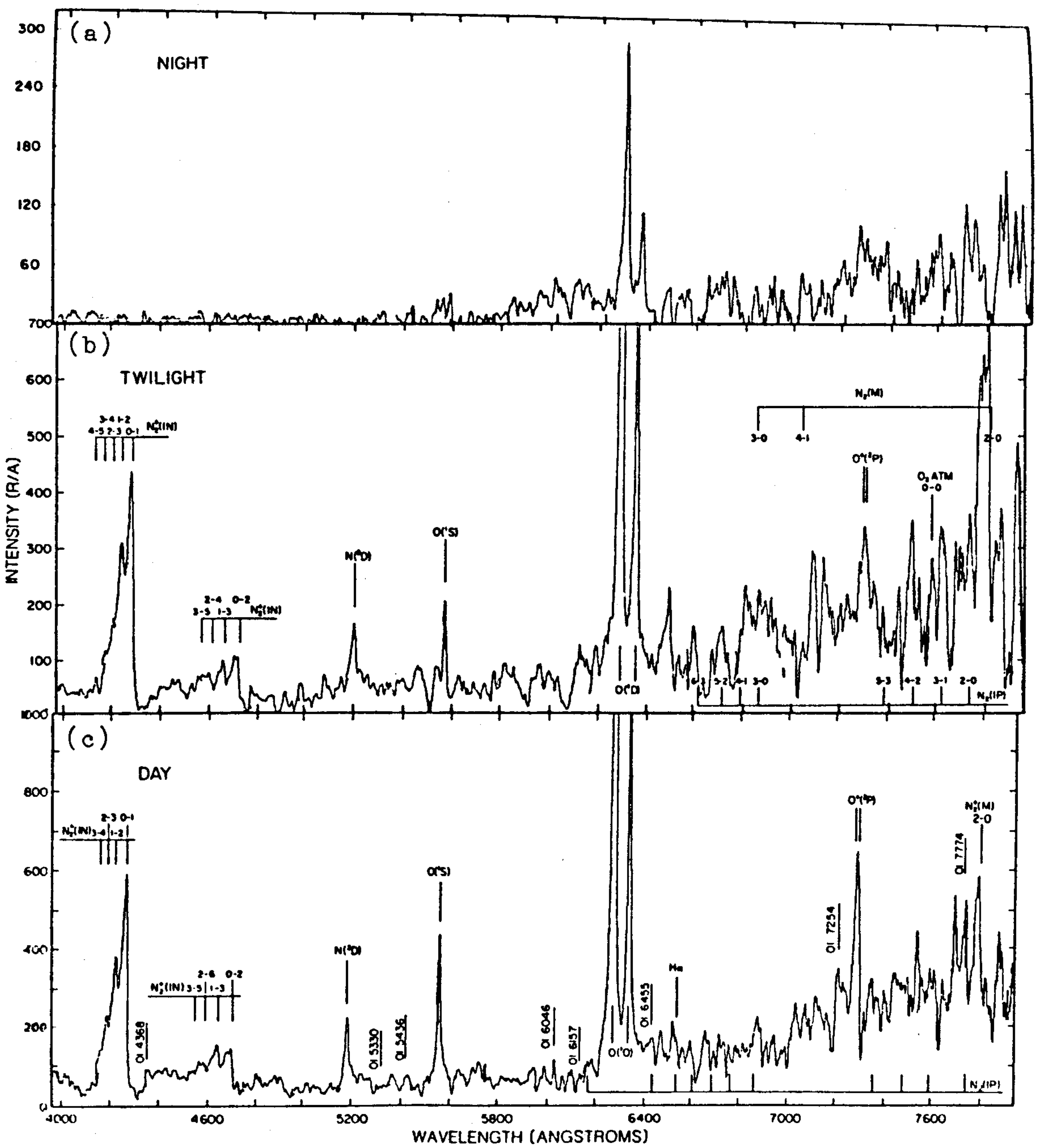


Fig. 16 The visible spectrum measured by the ISO Experiment on STS-9/SPACELAB 1.[56] Top spectrum (a) is for the wake on the nightside, the middle spectrum (b) for the wake at twilight, and the bottom (c) for the wake on the dayside.

Experiment (ISO) flown on STS-9/SPACELAB 1. Preliminary ISO results are reported in Refs. 40 and 56. Examples of the ISO results are presented in Figs. 16, 17, and 18 for several different look angles relative to the velocity vector and for the visible, near-UV, and far-UV spectral ranges, respectively. The ISO observed significant spectral emissions not of atmospheric origin in all orientations. The high-resolution spectral measurements of the ISO spectrometer demonstrated the presence of N_2 $a\,^1\Pi_g$ bands.[40,56] These may not be relevant observations as the spectrometer was oriented to study airglow and not at or along Shuttle surfaces. A number of emission features, which may be part of the natural aurora/airglow background environment and not representative of Shuttle glow, were also detected. Furthermore, there is the possibility that the glow may be from the surface of the instrument baffles.

Unfortunately, no imaging data were taken in conjunction with the ISO measurements, and therefore precise determination of the emission sources has been difficult. It may be that the ISO is measuring a glow associated with the Shuttle-induced contaminant cloud rather than the glow directly associated with a surface. This would explain the apparent wealth of spectral lines observed by the ISO, as opposed to the relatively featureless glow reported by Banks et al.[32] and Mende (e.g., Ref. 44), in that different processes might be involved. ISO also observed a glow in the wake of the Shuttle (see Fig. 16), again in contrast to the surface observations, where no glow was observed. Surface glow in the wake, if it is present, is at least two orders of magnitude weaker than surface glow in the ram direction.[2] Here we will refer to the glow observed by the ISO as a "cloud" glow to differentiate it from surface ram glow.

Ground-Based Observations

The only direct measurements of Shuttle atmospheric interactions in the near infrared were performed by F. C. Witteborn of NASA Ames with the ground-based 1.6-m telescope, Maui Optical Observatory, Hawaii. Witteborn's observations showed a glow in the IR range between 0.65 and 2.5 μm (peaking near 1.6 μm) and extending tens of meters from the Shuttle. His results, for nighttime observations of Spacelab 1, indicate that the glow flux density at 1.6 μm was 2.2×10^{-16} W cm^{-2}

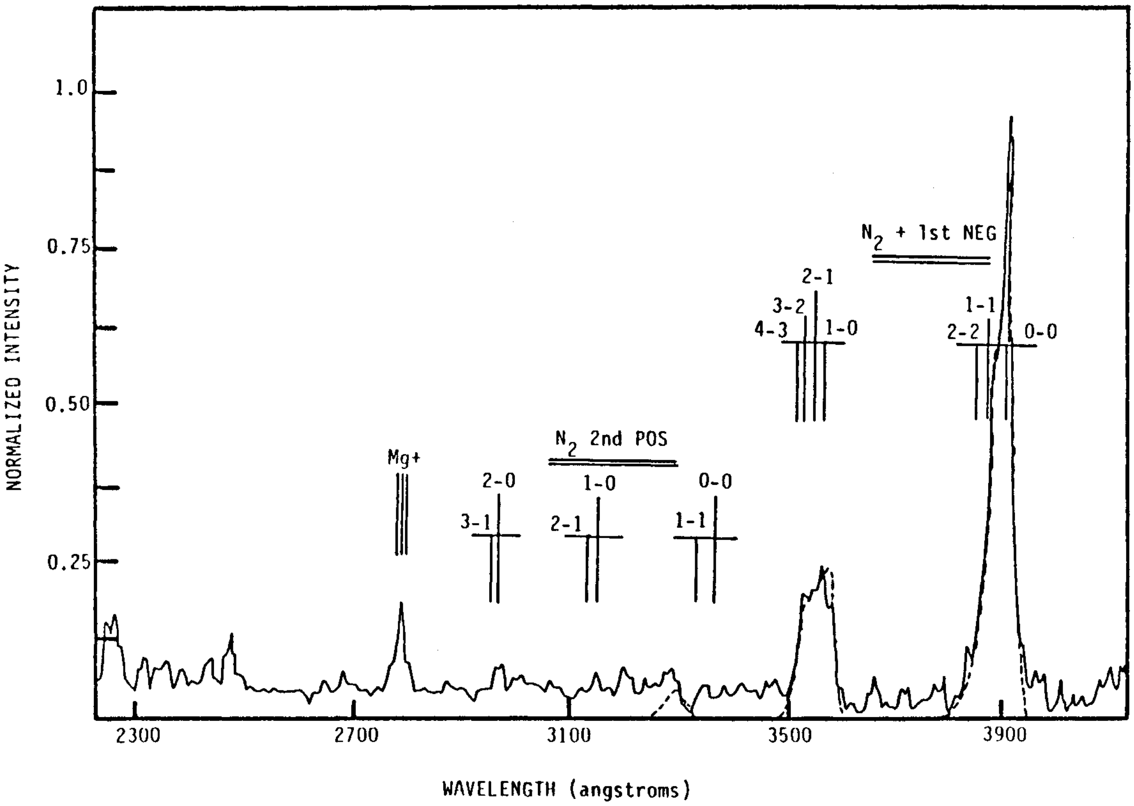


Fig. 17 Comparison of ISO ultraviolet data (solid line) from Spacelab 1,[56] with theoretical N_2^+ First Negative spectrum (dashed). The resolution is 18 Å.

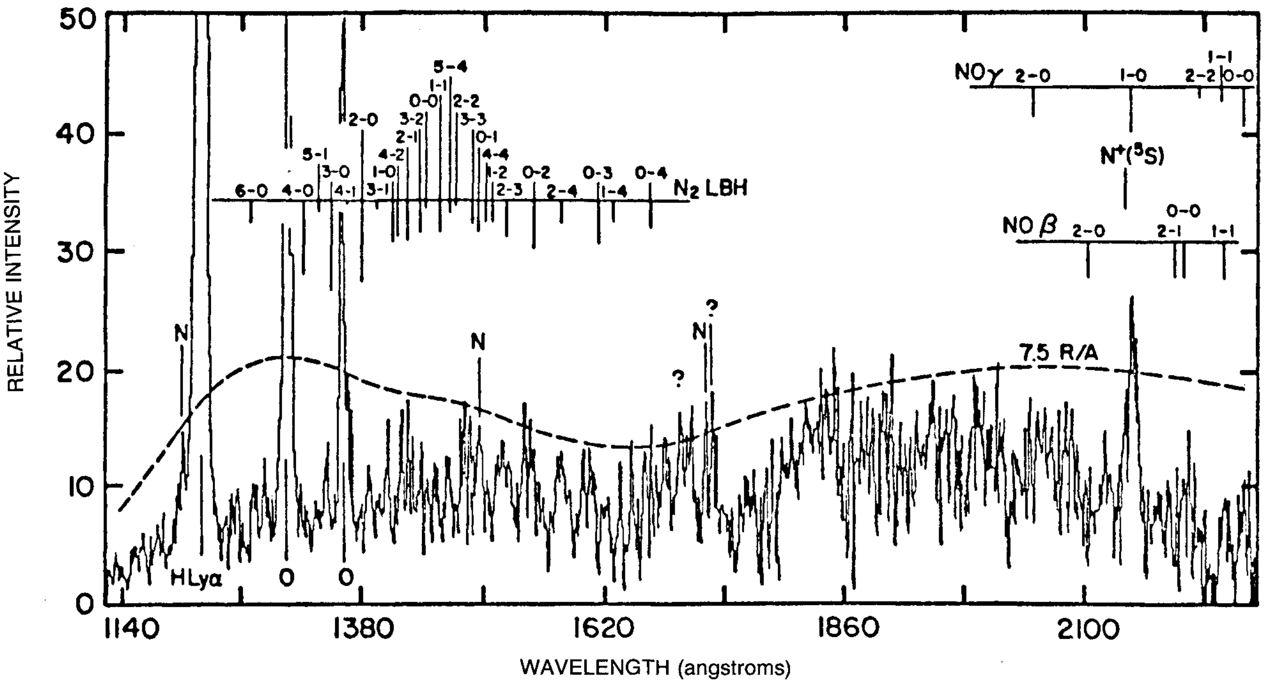


Fig. 18 ISO far-ultraviolet spectrum representing the average of measurements made looking into the velocity vector.[56]

$\mu m^{-1} sr^{-1}$ at 240 km, or about 220 times the value extrapolated from STS-3 data.[15] Such a flux density, or irradiance, would be about 5×10^{-9} W cm^{-2} μm^{-1} sr^{-1} at 400 km. This implies that, even at 400 km, the infrared "sky" over the Shuttle bay would be about 200 times the background zodiacal light (5×10^{-9} W cm^{-2} μm^{-1} sr^{-1} vs 2.4×10^{-11} W cm^{-2} μm^{-1} sr^{-1}), increasing the noise level at 16 μm fifteen-fold.

Thruster Effects

In addition to the surface-related Shuttle glow and the observations of the ISO reported above, there is a distinct glow phenomenon associated with Shuttle thruster firings. Banks et al.[32] first noted thruster enhancement of ram glow on STS-3. In particular, there is an immediate enhancement of the usual sur-

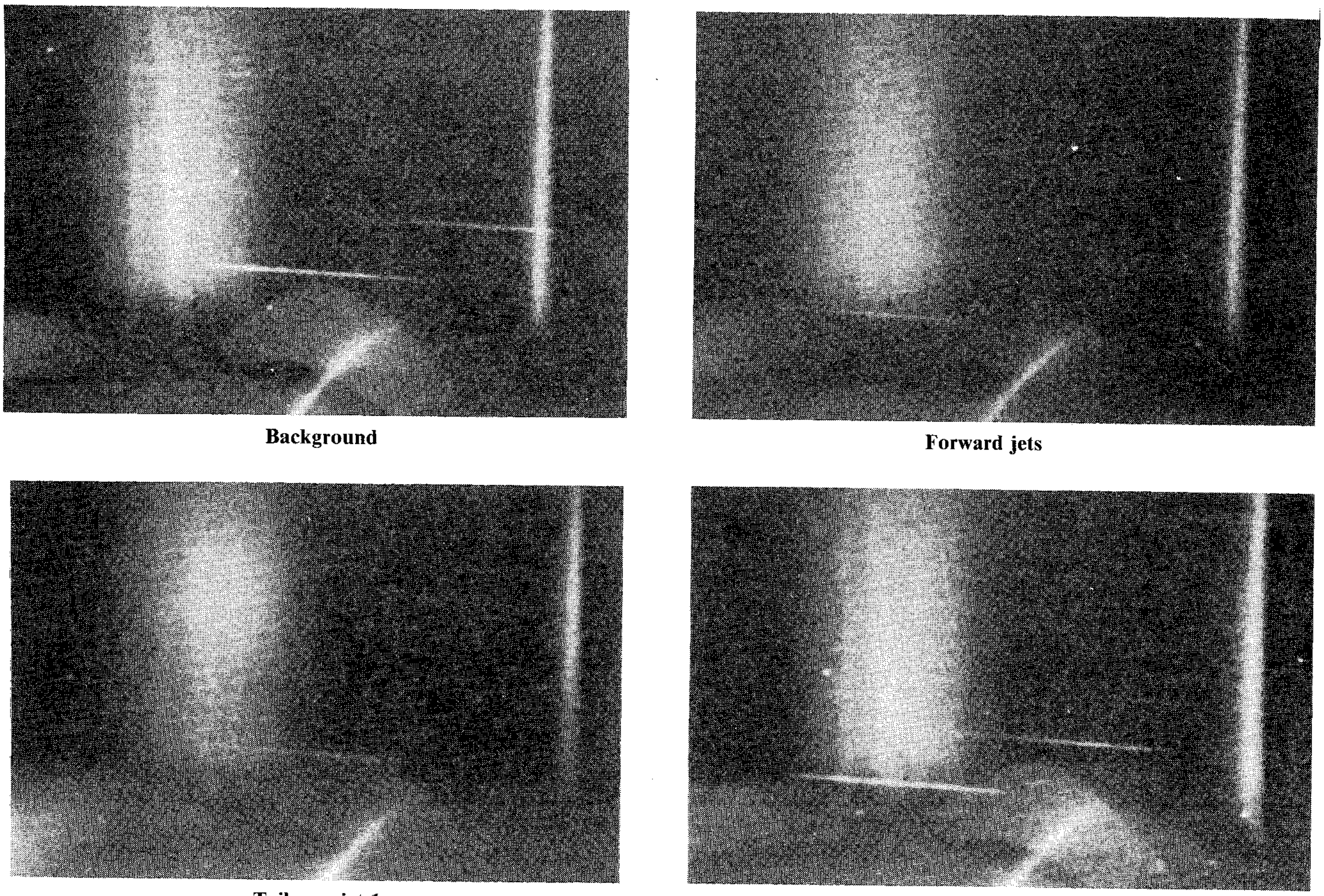


Fig. 19 Objective grating photographs of thruster firings on STS-8.[44] Top left frame shows the background for no thruster firings. The velocity vector is from the direction of the starboard wing.

face glow, followed by the creation of a glowing region apparently not associated with surface processes, that decays in tens of seconds. It has been suggested by Green et al.[57] that the thrusters emit a light flux of 10^6 R, caused by unburned fuel combining with ambient oxygen. A residual luminescence on the Shuttle engine pod surface was observed to decay with a time scale consistent with such oxygen-atom scouring of thruster contaminants trapped on the pod surface.[2] (See also Refs. 58 and 59.) Prince[60] has proposed that this residual luminescence may also be caused by a true surface emission (chemiluminescence) as a consequence of atomic and molecular oxygen adsorption.

As in the case of the Shuttle surface glow, Mende and his co-workers again have the most extensive Shuttle observations. For STS, Mende and Swenson[44] reported that the largest optical disturbance caused by thruster firings was created by downward firing of the tail thrusters (-ve pitch) (see Fig. 19). This presumably was because the tail thrusters fire toward the Orbiter wing, which collisionally thermalizes the exhaust gases, causing them to leave with low velocity relative to the Shuttle. On STS-8 (220 km), Mende and Swenson[44] found that the thruster-induced glow decayed with a time constant five times longer than that reported for STS-3 (240 km). The difference is possibly caused by variations in altitude and ambient conditions. The STS thruster intensity decay with time is presented in Fig. 20 for STS-3 and STS-8.

Serendipitously, Kendall and his co-workers[49,54,55] obtained spectra of a thruster firing on 41-G. Although the quiescent surface glow was too weak to be detected, they found the thruster-induced glow to be a continuum, at the 4-Å resolution level of their instrument, in the spectral range of 6275 to 6307 Å. They also found that the glow decayed slower on the surface than in the region over the surface (see Green's comments earlier in this section). This was interpreted as implying that the thruster glow consisted of two components: a surface component and a gas interaction that extended some distance from the surface.

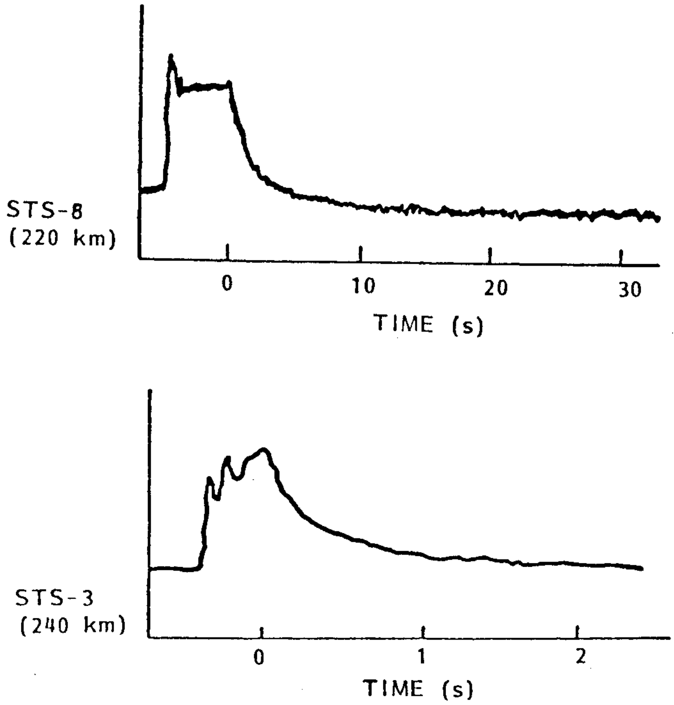


Fig. 20 Time dependence plots of the Shuttle thruster glow intensity on the engine pods following thruster firings (intensity is in arbitrary units).[44]

Theories and Scenarios

Observations of a glow within about a meter of the Shuttle and spacecraft surfaces in the ram direction have led to a number of interesting scenarios to explain this phenomenon. Theories (see Refs. 22, 26, 58, and 61-63) and reviews of theories (see Refs. 2, 61, 64, 65, and 66) abound on possible sources of the vehicle glow phenomena. This diversity suggests there may be several processes going on, perhaps simultaneously, that lead to different types of glow. The rich variety of explanations in turn has led to increased interest in such diverse areas as fast-atom sources, surface chemistry and physics, and vehicle-induced plasmas. There are at present, in fact, about 20 separate research groups in the United States preparing fast oxygen-atom beams by a variety of methods. (Charge exchange, photodetachment, and high-power laser dissociation are the principal means.) One interesting experiment[67] has detected a surface glow above Z-302 paint using fast (about 4- and 10-eV) beams of mixed N and N_2 extracted from a toroidal plasma. These results are indicative of the wealth of emission phenomena one can expect from fast beam-surface collisions.

In the following paragraphs we summarize several of the glow scenarios, pointing out the successes and the deficiencies in each. Green, in a series of papers, [2,61,65] has carried out extensive reviews of the theory of vehicle glow. Roughly following Green's general definitions,[65] at least six different classes of reaction processes can be identified:

1. Simple Gas-phase or Gas-solid Reactions Giving Rise to Excited Neutrals, such as OH^*[22]

In this scenario, for simple gas-phase reactions, ambient energetic neutral particles collide with the local environment and

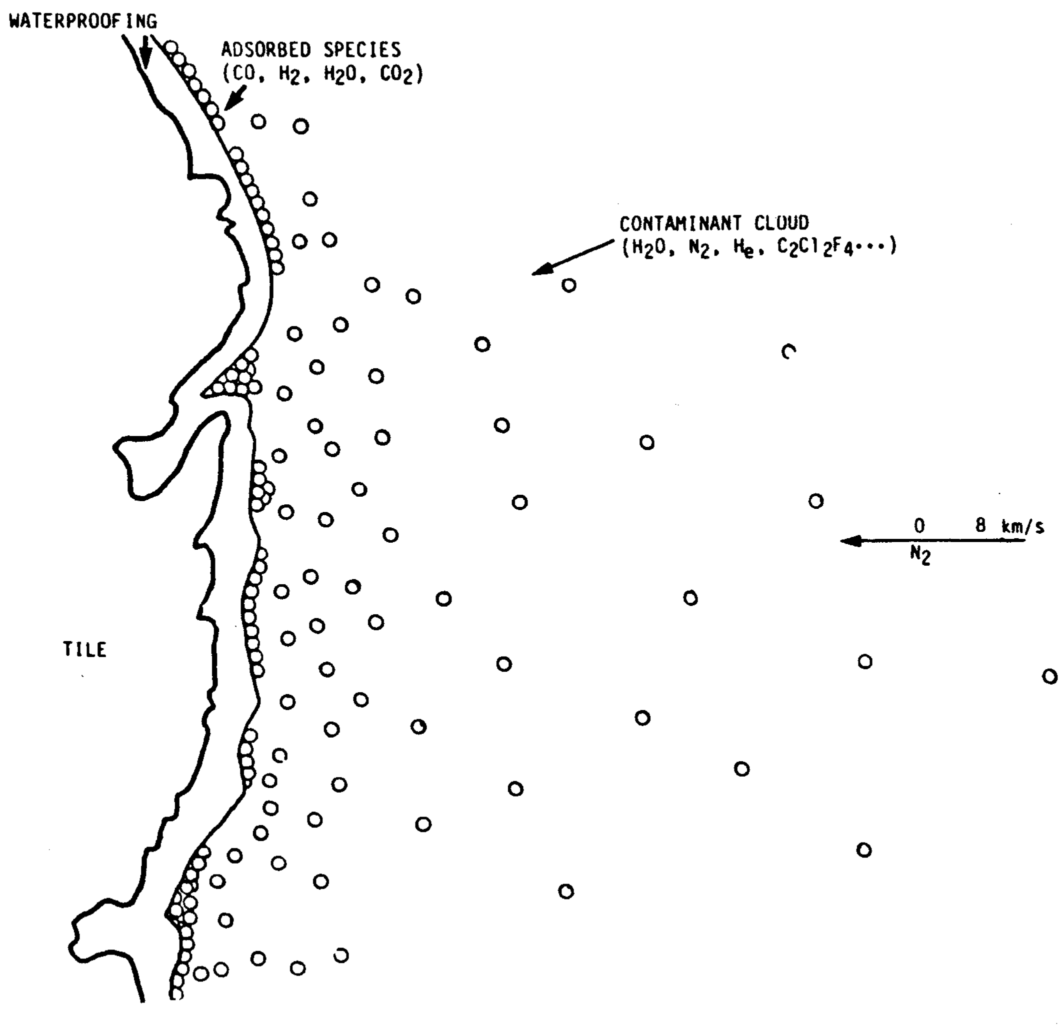


Fig. 21 Conceptual drawing of the interactions between gas phase/adsorbed species above Shuttle surfaces.[90]

react at the vehicle surface.[22,53] This is illustrated in Fig. 21. The incident particles collide with the vehicle cloud at 8 km/s, giving rise to energies ranging from 4.6 eV for N to 10.5 eV for O_2. Examples of the local environment are the reflected ambient particles (in which case up to twice the orbital energy would be available), the local contaminant cloud (from outgassing, water dumps, etc., discussed earlier), and thruster products. These gas phase collisions give rise to kinetic energy transfer and chemical and/or plasma excitation processes.[58] Possible radiators are vibrationally excited diatomic molecules such as NO, CO, and OH. Green[2] notes that these processes should be efficient at creating infrared emissions at levels of 10^5 R, but do not occur at a sufficient rate to generate visible glow for the observed levels of contamination. (Ram pressure buildup may, however, be able to generate a measurable glow.)

One proposed explanation for the thruster glow enhancements in terms of this type of process is that of collisions between the ambient atmosphere and the expanding plume molecules. A typical reaction control system (RCS) thruster firing results in about 10^{25} molecules of H_2O, N_2, and H_2 being released. Green[2] estimates that a megarayleigh (10^6 R) column intensity could be generated along the line of sight by such collisional interactions with this thruster plume cloud.

For molecular emission from surface collisions, the Langmuir-Hinshelwood process, which involves atoms adsorbing on the surface, migrating, reacting, and escaping in the gas phase, has been discussed. There is evidence from laboratory studies that atomic oxygen oxidizes carbon and enters the gas phase. If the surface is covered with adsorbed atoms, the incident atoms will react and escape in the gas phase in a Rideal process. In the Rideal process, when the surface concentration of adsorbed atoms is great enough, an incident gas-phase atom can strike an adsorbed atom so that the resulting molecule escapes in the gas phase. Produced in this process are O_2 and OH (both of which can emit in the red for excited levels).[68]

The glow observed on the AE and DE-B satellites is believed to be an example of interaction between gases and the bulk solid. It was observed early on that the intensity ratio of the glow measured on the AE satellites between bands centered on 7320 Å and 6560 Å is 2.15 between 170 and 175 km, and 2.25 between 140 and 145 km.[18,20,26] As this resembles the OH intensity ratio observed in the night airglow, Slanger[22] advanced the hypothesis that ambient oxygen (atomic oxygen primarily above 160 km), colliding with adsorbed water on the surface would produce excited OH. He found good correlation with the AE observations of Yee and Abreu[20] (Fig. 4) for an intensity given by:

$$\text{Intensity} = K_0[O(^3P)] + A\,[O_2]$$

where K is a proportionality constant and A is the factor by which 10 eV O_2 generates OH more effectively than 5 eV $O(^3P)$. Subsequent work[16,69] has demonstrated that a somewhat better fit is given by:

$$\text{Intensity} = K_0(\lambda)[O] + K_n(\lambda)[N_2]^2$$

where K_0 and K_n are functions of the wavelength λ. It is probable that parallel emission mechanisms are operant aboard the AE satellites, for example, the $NO_2{}^*$ recombination scenario, although this component could not be detected there.[69,70]

Additional support for the OH identification has come from Langhoff et al.[26] and Abreu et al.[25] The latter detected Doppler-shifted lines on the DE-B satellite that coincided with OH lines. Although not definitive, evidence seems to support Slanger's hypothesis that collisionally excited OH (most likely the Meinel bands) is the source of small satellite glow. As described next, Shuttle observations do not show similar agreement, so that OH emission has been ruled out as a major contributor for Shuttle surface ram glow.

A related explanation for Shuttle surface ram glow in terms of gas-solid reactions is that of Shimazaki and Mizushima.[71] In their scenario, ambient NO in low Earth orbit is collisionally excited by the ramming spacecraft surface to an effective vibrational temperature of 54,000 K (4.66 eV). These molecules vibrationally relax by radiative emission corresponding to large changes, Δv, where v is the vibrational quantum number. Those transitions occurring in the wavelength range of 4000 to 8000 Å correspond to $\Delta v = 7$ to 14. Arguments against this model are that 1) even at the coarse resolution used in the glow observations (about 34 Å), one would probably have observed a "bumpy" spectrum corresponding to groups of Δv lines overlapping and resolving, and 2) probabilities for such large changes in vibrational quantum number are small. Hence, lifetimes of such transitions are calculated to be large (about 3 ms or longer; see Fig. 6 of Ref. 71), whereas the optical decay constant of the glow for the Shuttle is estimated to be about 0.3 ms,[32] or one-tenth the required lifetime in this NO (v') model. A similar problem[51] arises with respect to the OH ($X\,^2\Pi$) vibrational emission model of Langhoff et al.[26] (discussed earlier) in interpreting the low-altitude Shuttle glow, although this model does account for emissions observed in the high-altitude AE-C and -E satellites.

The possibility of high-vibrational overtones in NO contributing to the Shuttle glow has been studied in some detail by Green et al.,[59] who also summarize the various chemical mechanisms that may contribute to the glow. In particular, they calculate the expected pure vibrational emission spectrum NO (X, v') $\rightarrow$ NO(X, v''), where $v' \le 19$, and $\Delta v = v' - v'' = 6$ to 9. The emissions lie in the wavelength range of 5000–8000 Å at a rotational temperature of 5000 K. When convolved with the proper slit function of the Swenson et al.[42] glow results, the calculated spectrum gives reasonable agreement with experiment. A "bumpy" spectrum is, in fact, calculated (point 2 above), a property that the authors claim is also inherent to the observed spectrum.

2. Surface-induced Decomposition of Molecules, Followed by Recombination into Excited Electronic and Vibrational States[58,61]

As a variation of process 1, Green has suggested that atmospheric N_2 could dissociate on impact with the satellite surface. He postulates that N formed by the impact will recombine and form N_2 in high vibrational levels and radiatively or collisionally decay, emitting lines in the N_2 First Positive system.[61] In this mechanism of recombining nitrogen atoms, N_2 molecules (bond energy of 9.8 eV) are dissociated by the 9.3 eV of energy associated with Shuttle surface impact. A portion of the relevant N_2 electronic states is shown in Fig. 22. The atoms recombine on the Shuttle surface into high-vibrational levels of the N_2 ($A\,^3\Sigma u^+$) state. A fraction of these $N_2(A)$ molecules leave the surface. They radiatively decay slowly into nearby levels of the (N_2 ($B\,^3\Pi_g$) state, and tehence quickly to levels of the A sttate. Questionable aspects of this model are

1) The Shuttle glow intensity scales as the O atom density [O] at altitudes of 160–280 km or more,[16] whereas this model would require scaling as [N_2].

2) Laboratory spectral emissions (see Fig. 2 of Ref. 61) show a pronounced double-peak character, whereas the Shuttle glow is single-peaked at 6800 Å.

3) The arguments for the lifetime of the $N_2(A,B)$ emissions are qualitative, and the model would apear to require a lifetime (not measured) for the $B \rightarrow A$ transition on the order of 0.1 ms in order to account for the spatial extent of the glow. In regard to aspect 1) above, it is interesting to point out that Dalgarno et al.[16] have indicated yet a third mechanism for the glow operant at altitudes less than about 160 km. This mechanism involves two N_2, O_2, or NO molecules. No details of a possible scenario are given.

The high-resolution (3–6 Å) emission spectra of the Shuttle environment reported by Torr and Torr[56] may support the N_2 mechanism. These spectra, as previously described, were taken from the payload bay, tangentially away from the Earth, and looking into the velocity vector. Only high-altitude (250-km) emissions occurring in front of the instrument, and away from the Shuttle skin, were recorded. In the wavelength range of the

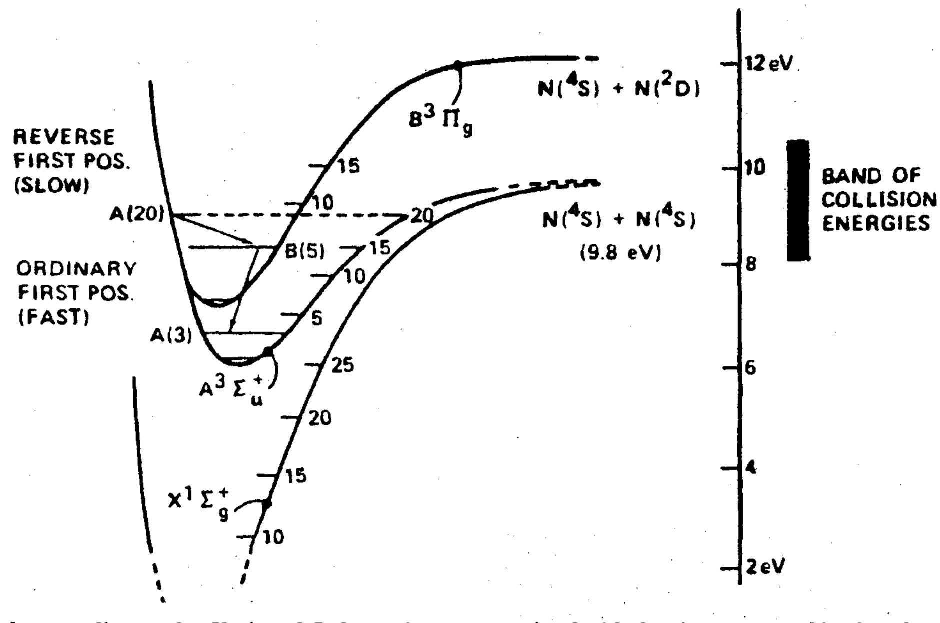


Fig. 22 The potential energy diagram for *X*, *A*, and *B* electronic states associated with the nitrogen recombination glow mechanism.[61]

Shuttle glow, these emissions included the N_2 ($B\,^3\Pi_g \rightarrow A\,^3\Sigma_u^+$) First Positive bands, and the OH ($X\,^2\Pi$) pure vibrational bands, with the bulk of the emission resembling the N_2 First Positive emissions reported by Green.[61]

3. Plasma Interactions

The Papadopoulos[62] plasma interaction model is based on a combination of beam plasma discharge and the critical ionization velocity that leads to enhanced ionization of the plasma surrounding the Shuttle. Neutral particles reflected from a satellite surface at low altitudes have nearly enough energy to be ionized in collisions with the incident ambient flux. Likewise, the high velocity of the neutrals and ions relative to the Earth's magnetic field may be sufficient to induce the Alfven critical velocity effect, which also contributes ionization. Given this enhanced ionization, Papadopoulos[61] proposed a plasma process for generating glow that involves a two-stream instability between the incoming ram and reflected ions. The ion instability generates electrostatic waves that heat the ambient electrons. These electrons excite the in situ and ram neutral and ion constituents. If the electrons are heated to 20-30 eV or higher, collisional excitation and ionization can occur. Papadopoulos estimates that there is sufficient energy to excite N_2 to the $C\,^3\Pi_u$ state and to ionize to the $B\,^2\Sigma_u^+$ state of N_2^+. He predicts that atomic and molecular ionic UV emissions could arise from these processes, whereas most of the chemical processes postulated to date will radiate most strongly in the red and the infrared. Unfortunately, the UV enhancement he suggests has not yet been observed and the theory does not predict exponential decay with distance from surface.

Kofsky[64] has reviewed the implications of this theory and finds that it is likely not a significant source of vehicle glow. In particular, Kofsky has countered that 1) the predicted spectrum of the Shuttle-surface discharge lacks the observed, strong orange-red component, and that 2) there are insufficient data on the makeup of the ambient neutral gas and on the ion-surface interactions to be able to quantify all emissions that would result from the beam plasma discharge. The plasma interaction theory has been further questioned in a recent study that correlated glow intensity and neutral density.[53] Photographs of the tail section (see Fig. 8) at different ram angles on STS-5 indicate that the glow is related to incident, fast neutral particles rather than to charged particles. However, as emphasized throughout this review, there may be several mechanisms that contribute to the rather ill-defined term "glow," and it is entirely conceivable that the plasma interaction model is one such mechanism, albeit a small one. Furthermore, the primary mechanism described in the Papadopoulos model[62] invokes plasma instabilities which lead to electron heating and enhanced ionization. It may still be a valid mechanism for producing these latter effects.

As noted by Kofsky,[64] UV spectroscopy is a good test of the plasma interaction theory in terms of electron heating, but may not, in itself, determine the magnitude (if any) of this energy input to the glow phenomenon. In fact, it is interesting to note that UV emission at 3914 Å, corresponding to the (0, 0) band in the $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ (first negative) system of N_2^+, has been used as a diagnostic technique in the laboratory study of the better known beam plasma discharge,[72] where a beam of energetic electrons is propagated into a neutral gas in the presence of a magnetic field. The term discharge is applied to both phenomena. It seems, however, that very little work has been done to define what this really means. By analogy with laboratory glow discharges, one is tempted to think in terms of an anode and a cathode, but apparently no attempts have been made to pursue this approach. If such an analogy were valid, then one might be able to make some predictions regarding the spatial distribution of the glow (or distribution of emitted light) and scaling in terms of the emission intensity/threshold for ignition with parameters such as electric field and pressure.

Kofsky also raises the question of the glow's day-night differences. Yee et al.[73] concluded that there was no correlation between glow intensity and plasma density as the AE-E satellite moved from day to night conditions. This would result in a difference in plasma density of approximately an order of magnitude. However, this conclusion is based on measurements at 7320 Å, whereas it is likely that the plasma mechanism will produce strong emission in the UV. Yee et al.[73] also point out that the AE satellite may be too small to produce a glow discharge and that their conclusion may not be applicable to the shuttle glow. This size or length scaling is consistent with the conclusions of Kofsky.[64]

Although Kofsky has given a rather thorough comparison of the plasma discharge model with observations, it would seem that a more rigorous analysis of the conversion of the discharge energy into light emission, taking into account all of the various plasma chemistry effects, is warranted. Although laboratory simulation of actual in situ conditions is extremely difficult, additional data could be obtained from laboratory experiments where one may control and vary parameters. A critical test would be observations with and without flowing plasma. An approach based on the analogy with laboratory glow discharges where cathode, anode, and current flow paths are defined is recommended as a fruitful path for future research.

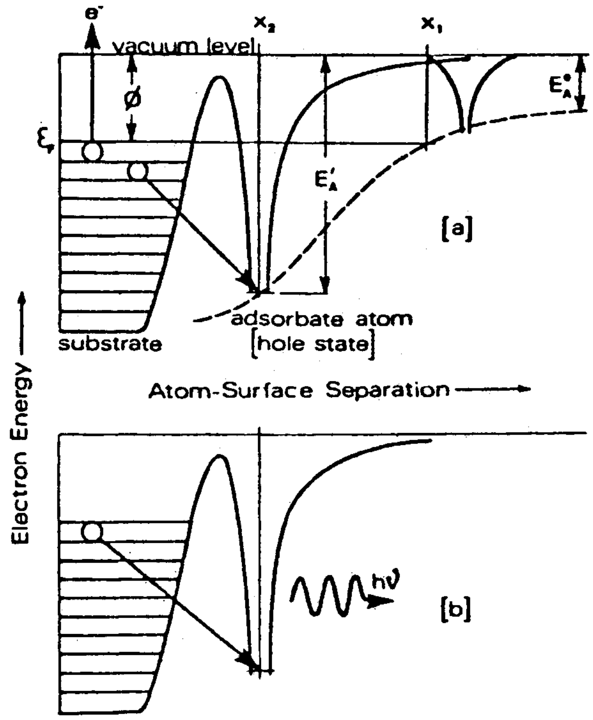


Fig. 23 Schematic of the process of filling a hole in an adsorbate state below the Fermi level, resulting in a) electron emission, and b) photon emission.[61]

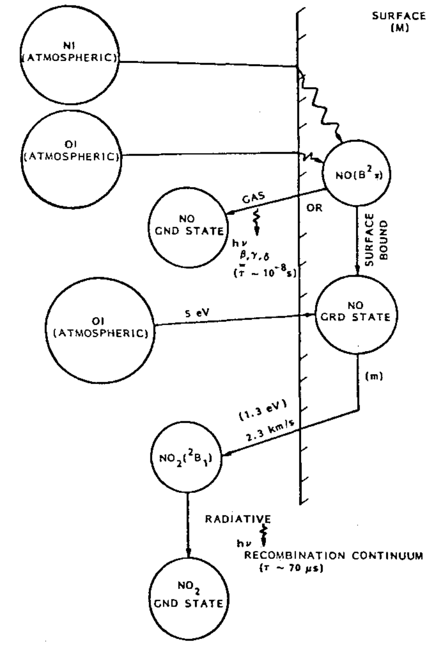


Fig. 24 Schematic of chemical processes that result in the NO_2 continuum emission believed to be responsible for Shuttle ram glow.[43]

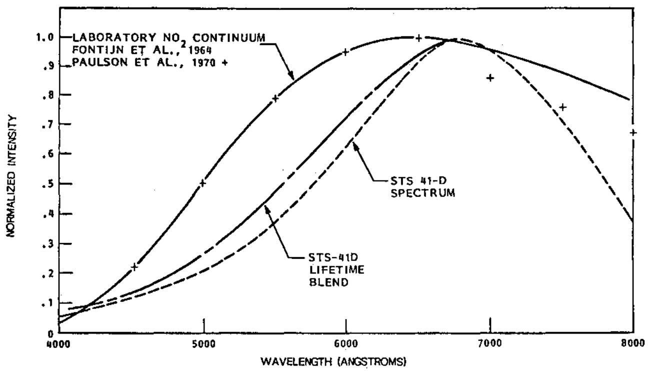


Fig. 25 Comparisons between laboratory measurements of the NO_2 continuum[78,82] and the STS 41-D spectrum. A spectral blend produced by e-folding the STS 41-D measurements with lifetime data from Schwartz and Johnston[91] is also shown.

4. Adsorption of O and O_2 on Surfaces

In the surface chemiluminescence model of Prince,[60] a second contribution to the continuum emission is proposed. This component is based on transfer of an electron from the Fermi level of the surface to the adsorbed, ambient species. If we denote the electron affinity of the adsorbate as E_A', and the work function of the surface as Φ, then continuum photon emission would be observed from energies of $E_A' - \Phi$ (where an electron from the top of the Fermi level fills the adsorbate hole) to zero (corresponding to a resonant transfer of electron to hole; see Fig. 23). This scenario predicts emissions shaded toward the red (peaking at about 6000 Å), and could account for the reddening of the glow noted by Slanger[22] at altitudes below 150–160 km.

In general, this type of interaction is extremely short-range (2 Å), so that the outer material surface greatly affects the process. One would expect this chemiluminescent component to vary with the type of Shuttle surface and even with the same surface as a function of time, both conditions affecting Φ. The work of Mende et al.,[3,46,52] however, shows that the glow intensity is not dependent upon the chemical stability or composition of the surface materials producing the glow, but rather on the environment itself. It appears that the reactants producing the glow are supplied to it. If, as has been suggested by Prince[60] and Kendall et al.,[54] O_2* residing on the surface were responsible, then one would expect to see a diminution of glow intensity with time in orbit. Such diminution is not observed. The process is, in fact, known to occur only above metals. Such variations and changes with type of surface and time, especially at altitudes below 160 km, have not been noted as far as we are aware, but should certainly be studied in future Shuttle flights. Green[2] refers to this as surface-aided chemiluminescence reaction with adsorbates.

5. The NO_2 Recombination Continuum Theory[4,42-44,74]

The NO_2 recombination process is a leading contender to explain the Shuttle surface glow. Sources of NO_2 are formation from NO by the so-called Eley-Rideal mechanism in the gas phase, or by the Langmuir-Hinshelwood mechanism mediated by a surface.[75,76] The component NO is present on the Shuttle surface from adsorption of ambient NO, by surface reactions of N and O, by O-atom reaction with Shuttle materials, or from thruster exhausts containing hydrazine or monomethylhydrazine.[59] The basic steps in the surface recombination process are illustrated in Fig. 24.[43] First suggested by Torr et al.,[17] surface recombination of atmospheric OI and NI is assumed to yield NO. Deactivated NO($X^2\Pi_{1/2,2/3}$) remaining on the surface can react with the ambient OI to form NO_2 ($\tilde{A}\ ^2B_1$) giving rise to the continuum $\tilde{A}\ ^2B_1 \rightarrow \tilde{X}\ ^2A_1$ emission[77] peaking near 6400 Å.[78] The NO_2 continuum thus generated, resembling the Shuttle surface glow, is a superposition of many states. If the recombined NO_2 retains 25% of the kinetic energy of the ram O, the thickness of the Shuttle glow layer can be explained by a NO_2 ($^2B_1$) continuum.[42] A portion of the NO escapes the surface. Assuming the escaping NO to be NO ($B\ ^2\Pi_r$),[79] then one might also observe the β-band emissions ($B\ ^2\Pi_r \rightarrow X\ ^2\Pi_{1/2,3/2}$) the spacecraft skin.[80] In fact, a wide variety of such desorbed, excited molecules is observed in laboratory experiments. Excited states of N_2, CO, CO_2, H_2, D_2, HD, D_2, OH, D_2O, NO, and NO_2 have been observed above a number of glass, metal, and metal oxide surfaces. These reactions, as well as a survey of the NO_2* electronic band spectra observed, are given in Ref. 4.

Further impetus for the NO_2* recombination scenario is provided by recent experiments of Arnold and Coleman.[81] Collision of a low-energy (0.16 eV) O atom beam with a nickel sur-

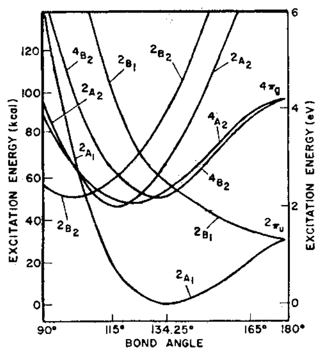


Fig. 26 Electronic energy as a function of bond angle for various low-lying states of NO_2.[82]

face, in the presence of NO, yielded an emission spectrum peaking at about 8200 Å. They conclude that the surface-mediated kinetics and the emission are consistent with the presence of electronically excited NO_2 formed at the surface.

This theory is not new. NO_2 continuum in a rocket wake was suggested by Heppner and Meredith.[1] NO_2 laboratory spectra of Fontijn et al.[78] and Paulsen et al.[82] are compared by Swenson et al.[42] with their 41-D spectrum of surface glow in Fig. 25. Differences between laboratory-produced (gas phase, single-collision) $NO_2(\tilde{A})$ and spacecraft-produced (surface-collision) NO_2 $(\tilde{A})$ could lead to differing vibrational level population distributions in the $\tilde{A}$ state and hence to a slightly different emission spectrum. However, as pointed out by Green and Murad,[65] such emission should scale as $[O]^2$ (one atom to form NO, a second to form NO_2), whereas scaling with [O] is observed.[16,22] The latter observation might be explained by noting that the NO_2 emission will not vary as $[O]^2$ if the N + O saturates on the surface at a given temperature, such as postulated by Swenson et al.[48] If the N + O creation goes faster than removal, but maintains saturation, the emission rate will be proportional to [O]. A laboratory simulation of the NO + O (^{3}P, 5 eV) reaction on an MgF_2 surface, followed by detection of above-surface NO* and NO_2* emissions would be a useful (although difficult) test of these hypotheses. In the case of NO*, the summary of Barrett and Kofsky[83] shows that the β-band emission has been observed from metallic surfaces. It is concluded that, under laboratory conditions studied to date (collisions of clean, model substrates with thermal O-atoms), desorption of NO_2* at any surface temperature appears to be an unfavored process. Actual desorption rates under impact with more energetic particles [5 eV O(^{3}P) atoms, electrons, or photons] could be quite different.

The expected emission intensities in the infrared of NO_2* ($^2B_1$, $^2B_2$) have recently been calculated.[74] These emissions are shown to result primarily from the ν_3 fundamental sequence near 6.2 μm and the $\nu_1 + \nu_3$ intercombination band near 3.6 μm. These bands have lifetimes that give (calculated) emission distances in the range of 60–250 cm. Studies of the UV β-band emissions of NO(B), and of the infrared pure vibrational emissions of NO (X), give characteristic emission distances on the order of 10^{-3} m and 10 m, respectively: either too short or too long to account for the observed spatial extent of the Shuttle glow. However, the NO(1,6) and (0,9) bands appear to describe the ultraviolet component of the AE ram glow.

In further support of the recombination hypothesis, the effects of skin temperature T on the glow reported earlier[48,49] would be consistent with greater accommodation of ambient, ramming species, and the subsequently formed NO, at the lower surface temperature. This would then lead to an increased glow intensity at lower T, as has been observed. Additional findings from DE-B also tend to support this hypothesis. By correlating mass-spectrometric measurements from the Neutral Atmospheric Composition Spectrometer (NACS) of NO_2 on a heated and cooled surface of the DE-B spacecraft, Engebretson[84] and

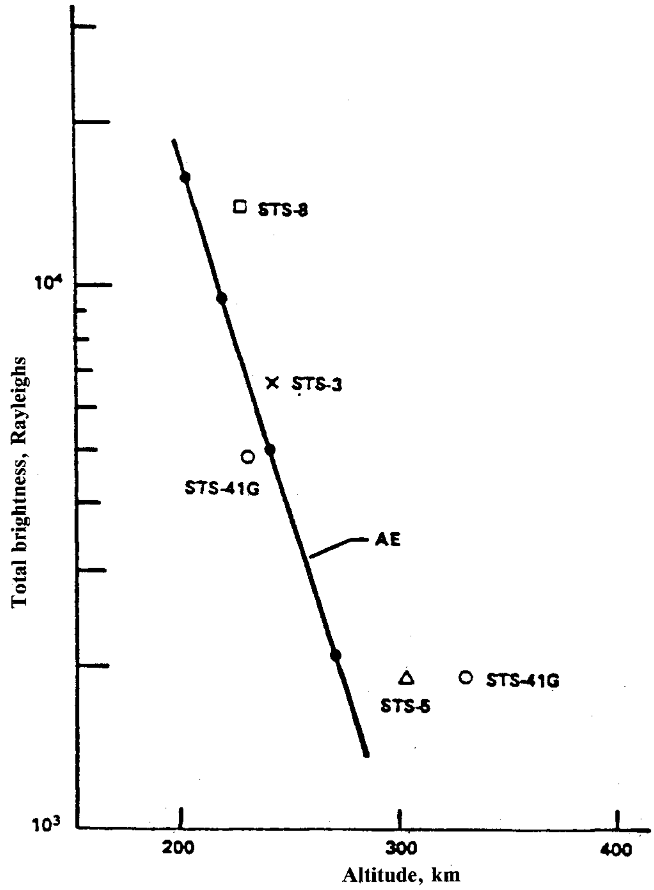


Fig. 27 A comparison of the brightness of the satellite (AE data) and Shuttle ram glows as a function of altitude.[89] **No correction for temperature has been made (see Fig. 15).**

Engebretson and Hedin[85] concluded that the glow was consistent with NO_2 continuum emission, resulting from a large number of excited, low-lying electronic states (see Fig. 26 and the NO_2 atlas of Hsu et al.).[86] A strong correlation of NO and NO_2 signals with ram direction was found for the open source ionizer design aboard the AE-C and -D satellites. Hence, it was also concluded that 1) direct exposure of the ion source surface to the ram direction is required for production of large amounts of NO_2, and 2) NO and NO_2, produced by surface recombination of NO and O, can form long-lived monolayers on the various Shuttle and/or satellite surfaces.[84] In addition to these findings, it should be noted that one of the key pieces of information that led Swenson et al.[48] to propose the NO_2 mechanism in the first place was the odd nitrogen chemistry and wall temperature catalysis reported in an earlier study of an on-orbit mass spectrometer by Engebretson and Mauersberger.[87]

6. Surface Bulk Reactions Leading to Material Loss or Composition Changes[64]

The same early missions that revealed Shuttle glow also revealed the existence of another serious problem for satellite surfaces: oxygen erosion. As reported by Leger and others (see review by Leger and Visentine[88]), atomic oxygen can remove as much as 10^{-3} cm of material during a typical Shuttle mission. Fortunately, the process is very composition-dependent. Thus, surface bulk reactions leading to material loss or change are a proven phenomenon. Green and Murad[65] have reviewed a number of such possible reactions for Shuttle surface materials. They find that reactions exist that cannot only produce material-specific glows, but can also change surface composition through nitridation, transformation from insulator to semiconductor, and alterations in thermal, structural, and electrical properties. Typical reactions involve compounds of silicon and carbon interacting with oxygen or nitrogen at the high impact velocities characteristic of the Shuttle to produce SiO_2, NO, and other more complex compounds. Green and Murad also discuss potential spectral implications. Specifically, they report that NO,CO, SiO, and CN could be released in the gas phase with sufficient excitation to emit. This could lead to a number of surface-specific glows and suggests that studies of such glows could yield valuable insight into surface property changes occurring in orbital materials.

Summary

The intent of this section is to summarize the findings presented previously. In that spirit, in Fig. 27 the glow surface brightness from several of the Shuttle missions has been compared with the AE glow measurements between 4278 Å and 7320 Å.[89] Although such a comparison is somewhat subjective, considering the possible geometric, thermal,[48] and temporal (i.e., changes in the ambient neutral density with solar activity) differences between the observations, the agreement is good, with the discrepancy associated with STS 41-G now being ascribed to a thermal effect (the surfaces were warm). Other features of the glow are summarized below.

Common Features

1) Ram glow is maximized on surfaces facing into velocity vector or ram direction. (Note: additional glows have been observed in the wake.)

2) The intensity of glow decays with altitude. In the case of AE-C, it decreased exponentially with altitude. The scale height was roughly 35 km, consistent with atomic oxygen at a temperature of 600 K. As illustrated in Figs. 15 and 27, there may be strong similarities in how the intensity scales with height between the Shuttle and satellites.

Satellite Glow

1) The glow increases in brightness toward the red.

2) Scale length of glow appears to be 1-10 m.

3) The angular variation with respect to the ram direction is proportional to $\cos^3(\phi)$.

4) OH (possible Meinel bands) is the proposed source of satellite glow.

Shuttle Glow-Ram

1) The glow is believed to be emitted over a continuum, rather than in discrete visible lines, extending throughout the visible, and having a peak intensity of 6800 Å.

2) The scale length of glowing layer in the ram direction is estimated at 20 cm above large flat surfaces on the Shuttle (perhaps only 6 cm above rms), which is consistent with an effective radiative lifetime of emitting molecules of about 0.6–0.7 ms for a mean emitter velocity of 0.3 km/s.

3) The intensity of glow varies from material to material, with black chemglaze (carbon-filled, urethane-based paint) and Z302 (overcoated with Si) being the brightest and polyethylene being the least bright. The scale length, however, is similar for each sample.

4) The angular variation with ram angle is closer to $\cos(\phi)$ than $\cos^3(\phi)$.

5) There is an apparent strong exponential correlation between surface glow intensity and surface temperature, with intensity increasing with decreasing temperature. In support of this, the weak AE satellite glow relative to Shuttle glow is consistent with the respective differences in surface temperature.

6) The most likely candidate is currently NO_2 recombination, resulting in a continuum emission from excited electronic states of NO_2.

Shuttle Glow-Thruster

1) The glow was enhanced after firing of the Shuttle's attitude thrusters. (Note: thruster effluents consist primarily of H_2O.)

2) The thruster-induced glow, measured at 4-Å resolution, was found to be a continuum in the wavelength range of 6275–6307 Å over which a measurement was made.

3) The ram glow, when enhanced by the thruster exhaust, decayed in a few seconds following thruster firings, with the time constant at 220 km being five times longer than that at 240 km.

4) Gas-phase or gas-solid reactions have been suggested as possible sources.

Shuttle Glow-Cloud

1) Observations looking directly away from Shuttle surfaces show a complex emission line/band spectrum not of atmospheric origin.

2) There may be significant glow in Shuttle wake.

3) $N_2\ a^1\Pi g$ bands have been suggested as the likely source of this glow.

Mitigation

Given the obvious diversity of phenomena, it is clear that much work still needs to be done in identifying processes and categorizing the effects of vehicle glow. Even so, some general mitigation guidelines are possible. First, the issue of satellite orbit is a major consideration. All studies imply that the Shuttle ram glow intensity decays with altitude, most likely because of the expontial decay of the atmosphere. If the mission cannot be flown at a high altitude, then other considerations, such as orientation of the velocity vector relative to instrument look angles, become important. Given the apparent rapid fall-off of ram glow with angle, it should be possible to select orientations for instrumentation which limit exposure to the Shuttle surface glow. In the case of Shuttle cloud glow, given the existence of line and band emission, filtering and careful wavelength selection for an optical sensor should likewise be an alternative. In the case of Shuttle thruster glow, limiting thruster firings during sensor operations or in the field of view of the sensor would be obvious alternatives. Finally, given the apparent dependence on surface material and temperature, careful selection of instrument baffle materials and coatings and control of surface temperatures would certainly limit the impact of the glow for instruments looking near the ram direction. Selection of appropriate materials and tests for temperature dependencies would be greatly facilitated by ground-based laboratory experiments using well-characterized beams of 5 eV $O(^3P)$ atoms.

Conclusions

Vehicle glow poses an across-the-board threat through the contamination of low-altitude optical sensor systems. The extent and systems impact of the phenomena associated with vehicle glow are only now being evaluated, with much work still to be done. The complexity of the phenomena dictates a varied approach to system design to mitigate the threat. Even so, with proper consideration of the glow parameters, it should be possible to develop means for limiting the impact on future low-altitude missions. Further in situ and ground-based laboratory experimentation and analysis are essential if this environmental effect is to be understood and ultimately eliminated as a survivability hazard.

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