Optical Environment of the Spacelab 1 Mission

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Large complex vehicles in Earth orbit, such as the Space Shuttle, represent major sources of offgassing contaminant release with potential impact on optical instrumentation operating from those vehicles. In addition, in recent years there has been a growing realization that the passage of an orbiting vehicle through the ambient environment generates emissions, both glows on or near the surface of the vehicle and halos surrounding the vehicle. Both of these induced emissions are of interest because they are as yet poorly understood and are of concern because of their potential to limit studies of the ambient environment and sources that must be viewed through the contaminant glow. The nature of the glows is not fully explained because many of the fundamental parameters required for such an understanding have not yet been measured. The causative mechanisms appear to be a complex function of altitude, time in orbit, materials, sunlight conditions, and vehicle size and orientation. While the Shuttle surface glows can be observed at times even with the naked eye, what is of concern to those involved with the design and use of sensitive optical instruments for space vehicles is the extent to which such instruments will be impacted, their use limited, and data interpretation compromised by the induced optical environment in general. This paper discusses what was learned about the contamination environment from the complement of instruments on the Spacelab 1 Shuttle mission and outlines the measurements needed in order to obtain an understanding of the processes involved and to predict these limiting effects.

Introduction

The question of to what extent a structure in space may contaminate its optical environment through induced emissions is of concern and interest to all those who must operate from these platforms for scientific or monitoring purposes. Over the past two decades, there have been several reports of unusual and unexpected optical effects in the vicinity of vehicles in space, culminating in the very pronounced surface glows and other forms of optical contamination in the case of the Space Shuttle. The very bright glows generated on or near surfaces directed into the velocity vector[1] are an obvious factor for instruments that must operate in this orientation. However, it is important to have quantitative information on the contamination environment in general and its dependence on such parameters as orientation, altitude, and time.

In this paper we shall summarize what has been learned in this regard from the various optical instruments flown on the Spacelab 1 mission.

Quite apart from emissions that might be excited by mechanisms utilizing the relative energy of the vehicle and the atmosphere (8 km/s) or surface catalysis, a vehicle such as the Shuttle is capable of introducing a fairly exotic mix of constituents into its environment. Table 1 shows the composition of the Shuttle exhaust. In addition to these contaminants, there is the offgassing of vehicle and payload materials, together with species absorbed on vehicle surfaces while on the ground (such as water vapor, salt spray) and leaks from various Shuttle and payload systems that must certainly occur from time to time (for example, freon from the coolant loop). Adding further to this mix is the H_2O released in the water dumps, which takes the form of water vapor or ice particulates. Articulation of mechanical devices in the cargo bay carries with it the potential for generating dust particles.

Table 1 Reaction control system motor characteristics[a]

Propellant	MMH/N_2O_4
Oxidizer/fuel ratio	1.6
Thrust, 1b	
Primary	870
Vernier	24
Plume specie mole fractions	
H_2O	0.32
N_2	0.30
N_2	0.17
CO	0.13
H	0.023
OH	0.015
NO	0.002
O	0.001
O_2	0.0009
Dribble volume	5 $cm^3 MMH_{(\ell)}$ $N_2O_{4(\ell)}$

[a]From Ref. 2.
[b]ℓ(primary) 4 and 7% of effluent for 80 ms pulse.

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Table 2 Optical instruments on spacelab 1

Instrument	Type	Location/ viewing direction
Solar		
Active cavity radiometer (R. Willson)	Three-channel cavity pyrheliometer	Pallet/-z, solar pointing
Solar constant radiometer (D. Crommelynck)	Two-channel pyrheliometer	Pallet/-z, solar
Solar spectrum (G. Thuillier)	Three double spectrometers (170-3200 nm)	Pallet/-z, solar
Atmospheric		
Grille spectrometer (M. Ackerman)	2.5-10 um	Pallet/ +y, solar
Hydrogen Ly-α (J.-L. Bertaux)	1216 Å	Pallet/-z
Imaging Spectrometric Observatory (M. R. Torr)	Five spectrometers (300-8000 Å)	Pallet/-z, -y
Atmospheric emissions photometric imager (S. B. Mende)	Visible filter photometer (2800, 3914, 4278, 5577, 6300, 7774 Å)	Pallet/scannable
Astronomy		
Wide-field camera (G. Courtes)	Ultraviolet film camera	Spacelab airlock/-z
Far ultraviolet stellar Telescope (C. S. Bowyer)	Ultraviolet film camera	Pallet/-z
Earth observation		
Metric camera (M. Reynolds)	Visible film camera	Spacelab airlock/-z
Contamination		
16 mm cameras/IECM	Visible film camera	Pallet/-z
Crew-operated imager (S. B. Mende)	Visible	Shuttle AFD window
Optical samples/IECM	Various coatings	Pallet
Ground		
AMOS observations of Shuttle (F. Whitteborn)	Near-infrared (1.6-2.3 μm) (1.6-2.3 μm)	Hawaii

Given this situation, we should not be surprised to find that vehicle effects limit observations at certain times. However, assessments made prior to the STS and Spacelab 1 flights predicted that materials released by the Shuttle would rapidly be left behind and that thruster firings would be of millisecond durations. Our interest here is to examine the available evidence as to whether these predictions are borne out by the optical data.

The results do not allow definitive conclusions to be drawn, because only partial information on the induced emissions exists and insufficient fundamental parameters on the glows and halos have been measured. We outline the measurements that must be made to permit an adequate interpretation. A workshop on spacecraft glow and related issues was held at the NASA Marshall Space Flight Center in 1985.[3] We have drawn on discussions at that workshop and its recommendations in arriving at the needed measurements.

Optical Results from the Spacelab 1 Mission

The Spacelab 1 scientific payload included the optical instruments listed in Table 2. Brief descriptions of these instruments may be obtained from Refs. 4 and 5. These instruments cover a broad wavelength range and it might be assumed that combined they provide a significant capability for the diagnosis of vehicle-induced optical contamination. In fact, however, many of these instruments were designed to observe high signal levels and so were not sensitive to induced emissions at levels that might impact studies at low light levels. Others were specifically located on the vehicle so as not to view any Shuttle or payload surfaces, leading to some ambiguity as to whether unanticipated features are ambient or induced and, if induced, whether the emission is from surfaces within the instrument or from the gas volume somewhere in the instrument field of view. Finally, typical observing sequences were not scheduled with instrument fields of view looking into the velocity vector where the largest induced effects might be expected.

We have queried each of the optical instrument teams listed in Table 2 as to whether or not their data contained evidence of vehicle contamination of any form. The following is a summary of the responses.

Several instruments showed no indications of contaminant signatures in their fields of view. The infrared grille spectrometer, which operates in a solar occultation mode, has provided upper limits on several species, as follows: 10^{14}cm^{-2} for CO_2 and 10^{15} cm^{-2} for H_2O, O_3, CH_4, NO, NO_2, N_2O, HF, HCl, and CO, although these upper limits represent very high column concentrations. The Lyman$-\alpha$ experiment that measured hydrogen and deuterium in the atmosphere saw no sign of vehicle-induced effects; neither did the imaging photometer (AEPI) nor the ESA solar constant radiometer.

Other instruments were affected by unexpected sources of light, but these effects cannot be definitively attributed to vehicle contamination at this point. A NASA instrument designed to measure the solar constant (the active cavity radiometer) has reported that all of the data taken on the Spacelab 1 mission were flawed, either by contamination or by some unidentified object occulting the field of view. Two ultraviolet astronomy cameras both found their film to be fogged. An initial assessment attributed this to Shuttle-induced ultraviolet emissions. However, after an in-depth look at the overexposed frames brought back by the FAUST

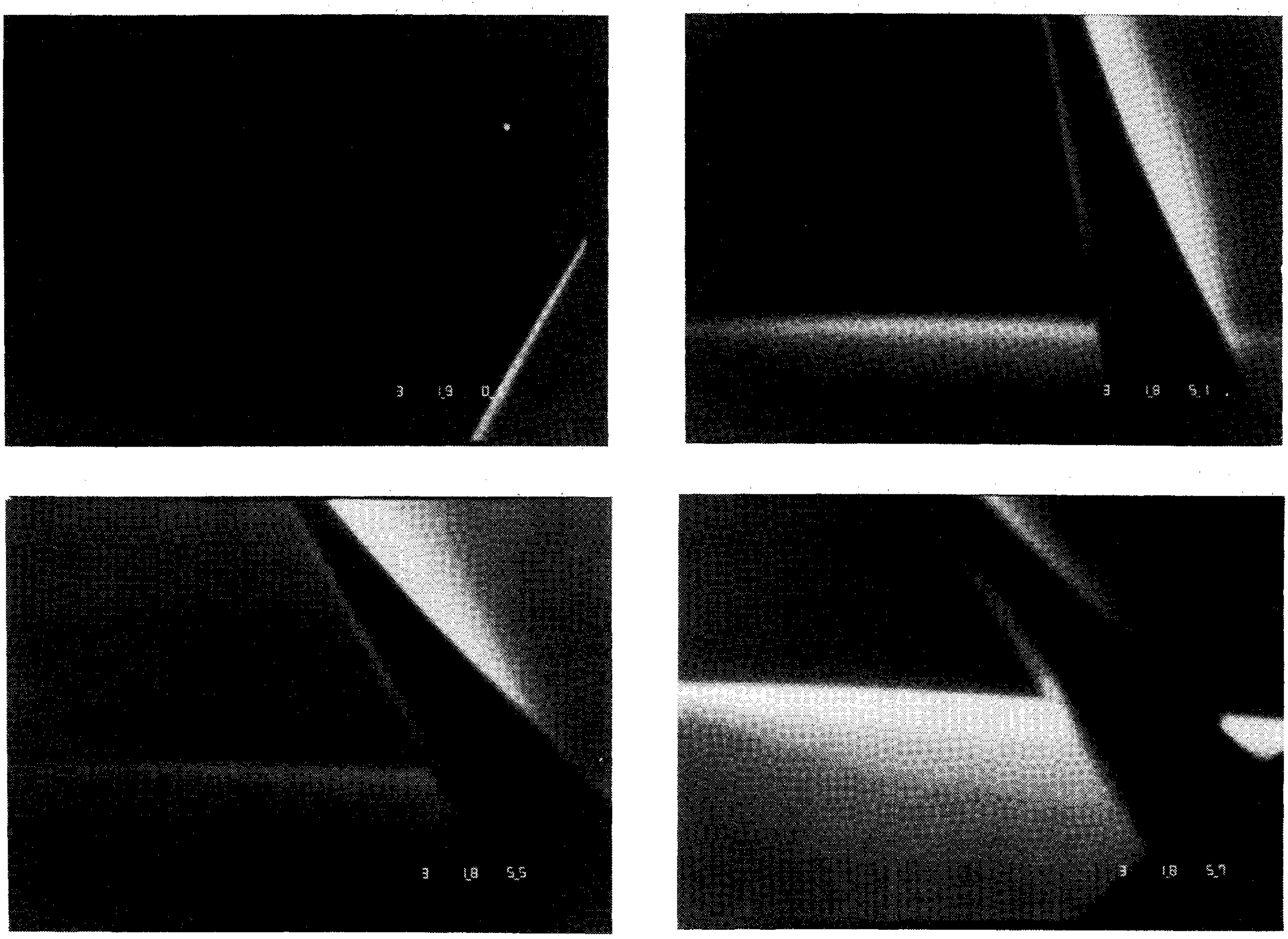

Fig. 1 Photographs taken on the Spacelab 1 mission from the aft-flight deck window using a hand-held intensified camera. Wavelengths are: upper left, 4800 Å; upper right, 5577 Å; lower left, 6300 Å; lower right, 7620 Å. (Courtesy: S. B. Mende.)

experiment, the investigators could not find a solid statistical link between the background film density and viewing direction. Such a link would have supported a ram induced emission source, such as glowing surfaces. Although a "halo glow" surrounding the vehicle cannot be ruled out, the general background level viewed by the instrument was found to be consistent with the 1304/1356 Å tropical arcs being the major contributor.

A hand-held imager operated by the crew from the aft-flight deck window confirmed that surfaces directed into the velocity vector on Spacelab 1 did glow as on the earlier missions. The brightness of the tail fin relative to the airglow at several wavelengths is shown in Fig. 1. Several measurements have been made of the glow using this camera on different Shuttle missions and are described by Mende and Swenson.[6] The data obtained on the Spacelab 1 mission were used to confirm the scale length of the near-surface glow to be ~20 cm. Mende and Swenson[6] have reported that the glow is a continuum to within the 34 Å spectral resolution of this instrument, peaks near 6700 Å, and has a brightness converted to normal to the surface of 1 - 10 kR.

The Imaging Spectrometric Observatory (ISO) was designed to operate at low light levels to measure atmospheric emissions from the vacuum ultraviolet to the near infrared. The spectra obtained with this instrument contain several features that would not be expected form the ambient atmosphere.

The $N_2{}^+$ ions as measured by the $N_2{}^+$ first negative band system were found to have unanticipated vibrational and rotational distributions. An example is given in Fig. 2, which shows the $\Delta v = -1$ progression of the $N_2{}^+$ ion system. Also shown in the figure is a synthetic spectrum computed using the ~3500 K resonance fluorescence model that represents the prevailing understanding of the major excitation mechanism for this emission in the dayglow. As can be seen from the figure, the spectrum measured from Spacelab 1 is both rotationally and vibrationally enhanced. Many of the constituents that might be introduced by a space vehicle into a contaminant cloud are the same as those occurring naturally in the atmosphere; thus, it becomes difficult to distinguish the natural from the induced contribution to a particular emission unless the intensities are anomalously high or there are other characteristics, such as unusual population distributions.

Examples of spectra obtained with the ISO looking into the velocity vector were reported by Torr and Torr.[7] While some additional ram data have been processed from this observation set since that time, the nature of the spectra remain essentially the same. The most obvious characteristics are that the $N_2{}^+$ ion emissions show very unusual population distributions, there are emissions between 6000 and 8000 Å that are not clearly identified, and there are some features throughout the spectrum that are yet to be identified. A synthetic spectral analysis of the ram data will be published elsewhere.

In addition to the measurements made by the scientific payload on the Spacelab 1 mission, an engineering package known as the induced environment contamination monitor (IECM) was also flown. This contained a pair of 16 mm cameras mounted in a stereoscopic configuration.[8] These cameras obtained a frame (of variable exposure, depending on the brightness of the field) every 2.5 min throughout the mission. Examples are given in Fig. 3. The record obtained reveals a rather severe particulate environment over a significant portion of the mission duration. A comparison of the particulate environment during the Spacelab 1 mission with that on the earlier STS flights is shown in Fig. 4.

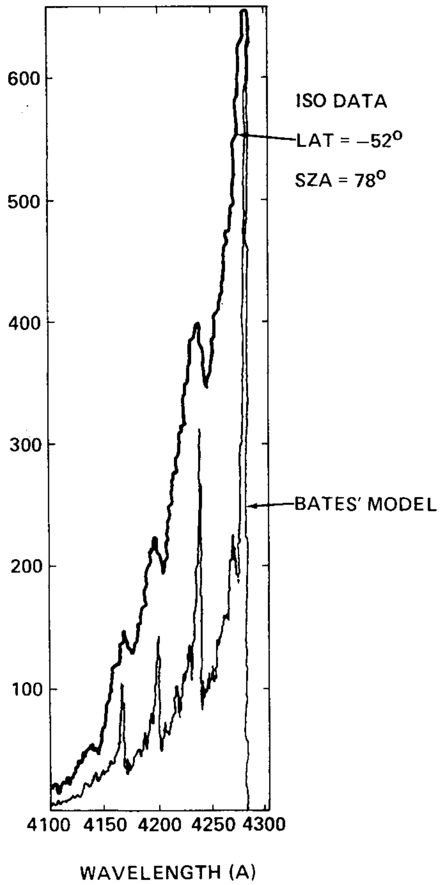

Fig. 2 Vibrational distributions for the N_2 ^{+}B state from the Spacelab 1 data vs those predicted by theory.

During the Spacelab 1 mission, observations were made from the ground in the infrared using the AMOS tracking facility on Maui. The measurements were made at 1.6 and 2.3 μ.[11] The integrated brightness of the Shuttle at 1.6 μm was found to be equivalent to that of a +6.6 magnitude star; at 2.3 μm, the brightness was typical of scattered thermal radiation from the Earth's surface. Thus, at 1.6 μm, the brightness is some 200 times that of the zodiacal background. Subsequent observations of Spacelab 2 found the brightness to be 8000 times that of the zodiacal background. In both cases, the glow appeared to extend several Shuttle lengths from the vehicles.

Some other data of optical relevance are available from the Spacelab 1 mission. The grille spectrometer made observations using a 20 × 50 cm gold-plated mirror that was directly exposed to the environment during measurement sequences. No significant alteration in the optical properties of this mirror was measurable. The ISO extreme ultraviolet spectrometer contained a well-baffled, osmium-coated grating. While exposed osmium surfaces are now known to disappear within a few days, the osmium surface within the ISO instrument did not show a major deterioration, i.e., more than 30%.[12] The ISO instrument, when examined postflight, showed relatively little evidence of its almost 2 years at the Kennedy Space Center and 10 days in orbit, with subsequent landing and handling. Particulates were found on external surfaces, a number of which were black, soot-like particles. The white ß cloth outer covering of the thermal blanket had darkened in places. This effect was also found on other thermal blankets and has been reported to be due to a substance used in the manufacture of the ß cloth to keep the fabric flexible.

The discoloration, however, was found to be more pronounced on certain sides of instruments, indicating a directional dependence. In addition, both Velcro strips and fiberglass washers in these areas had changed from white to brown, with the latter very brittle. The overall instrument performance was found to be similar to the predelivery condition

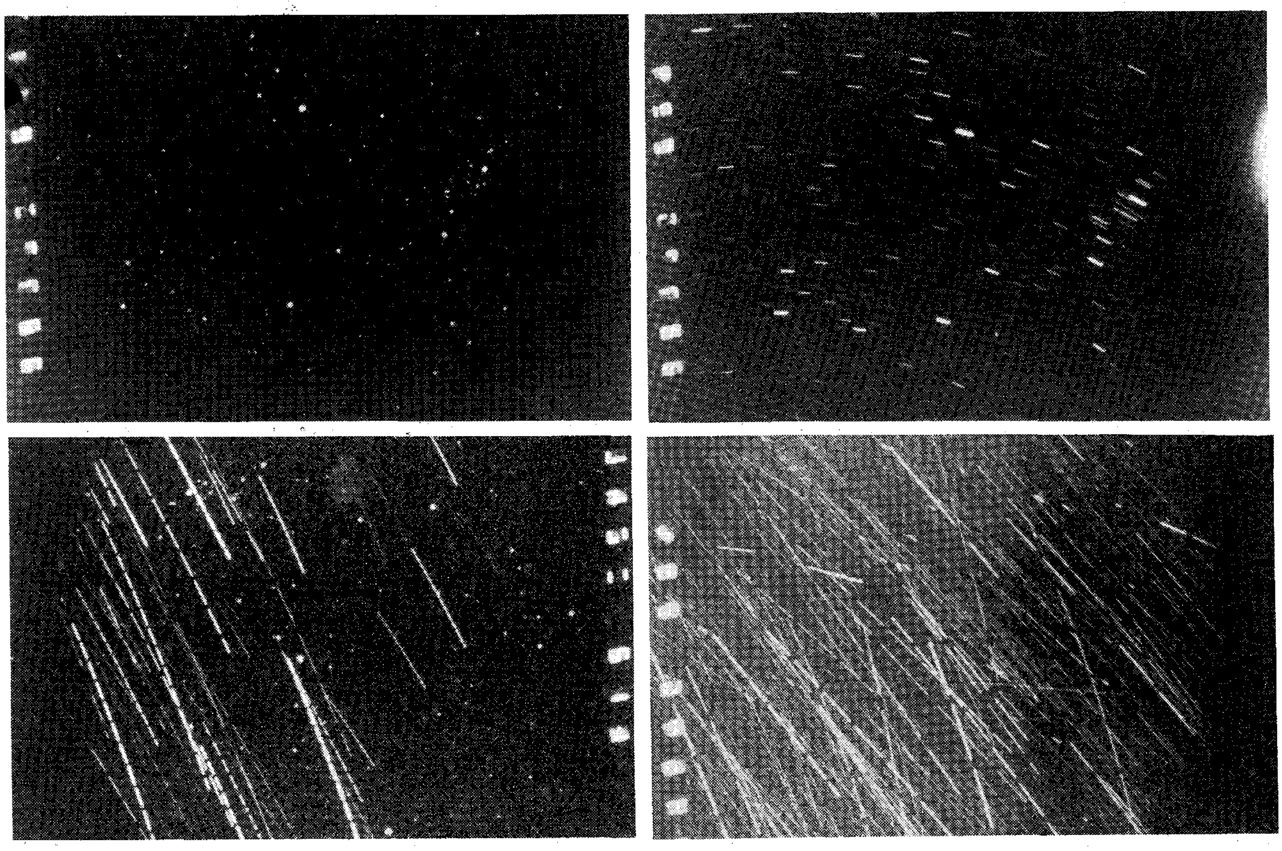

Fig. 3 Four frames taken with 16 mm camera on Spacelab 1 (39 deg field of view): upper left, star field; upper right, star field smeared by vehicle maneuver; lower left, particulates moving across field of view against stationary star field background; lower right, large number of particulates, some moving in different directions from others. The "dashed-line" appearance of the particulate trajectories is due to the fact that the camera shutter closes once a second and these are exposures of several seconds.

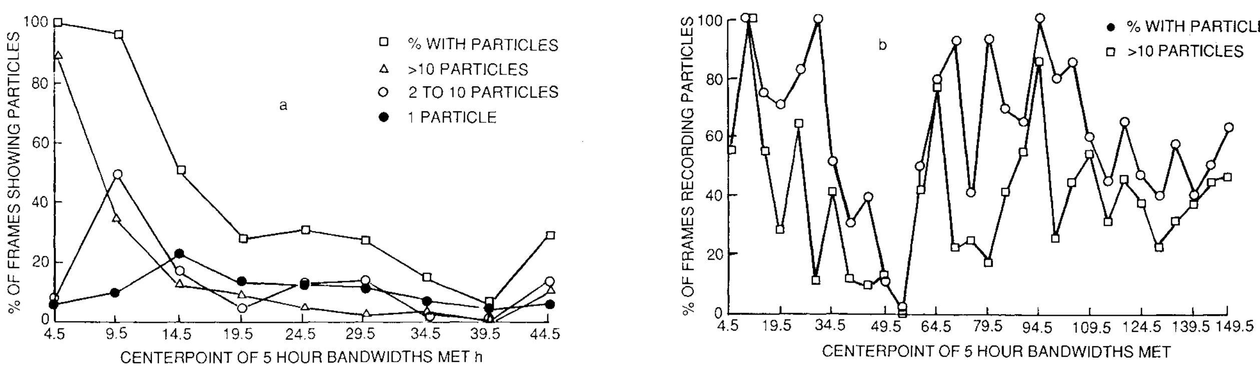

Fig. 4 Percentage of camera-photometer frames showing particles for: a) STS-2, STS-3, and STS-4; and b) STS-9.[8,9]

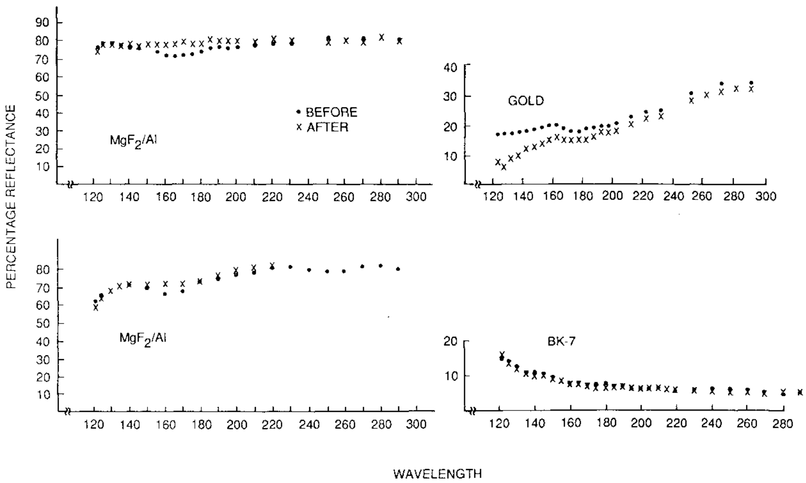

Fig. 5 Passive sample array pre- and postflight reflectance measurements (from Ref. 10).

to within the ±30% uncertainty of the comparison. The instrument was double-bagged, sealed, and purged with GN_2 at all times prior to launch. In order to allow the spectrometer cavities to repressurize on re-entry, long-path-length micropore filters were built into the shell of the instrument. One of these filters was analyzed postmission for captured volatiles and was found not to differ significantly from an unused filter that had not flown (and had been sealed and stored since the purchase of both filters).

A mass spectrometer in the IECM package[10] found the water column density to be 1-2 × 10^{12} cm^{-2} and measured a higher than expected partial pressure of He and Freon-114, both attributed to leaks. Details of the Spacelab 1 IECM results have been reported by Miller.[10] This package also contained a passive array of various reflective and transmissive samples. While the transmissive samples did not show significant change or evidence of contamination, the reflectance results, summarized in Fig. 5, did show changes. The aluminum mirrors with an overcoating of magnesium fluoride showed evidence of an increased reflectance near 1600 Å. The gold mirrors showed significant degradation (50% at 121.6 nm). Small changes were found in the reflectance of a BK-7 glass sample.

Discussion

In the light of the present information, we can draw the following conclusions. Surfaces directed into the velocity vector glow intensely, at times bright enough to be visible to the naked eye. One would thus expect the interior surfaces of instruments directed into the velocity vector to also glow, particularly as commonly used black paints glow brightly. Measurements made by Mende et al.[13] show the spectral character of this surface glow to have the appearance of an orange-red continuum. With the exception of the active cavity radiometer, instruments designed to look at bright sources do not appear to have been impacted by induced glows, although it should be borne in mind that, apart from the example discussed above, all observations taken on the Spacelab 1 mission were designed to avoid looking into the velocity vector. In addition, contamination monitors, such as CQCM's and optical surface tests, show that any accumulation of large-mass molecules was low. Most effects are therefore at the level of very sensitive instruments and, indeed, it is these instruments on Spacelab 1 that have reported a variety of spurious optical effects — some of which may or may not be vehicle related, but some of which certainly do not appear to be explainable in terms of known ambient sources. Some of these effects would require an extended glow or halo entirely surrounding the vehicle, possibly to a distance of some meters.

Recently, two quite different models of the Shuttle environment have indicated that the "Shuttle glow" may not just be a near-surface phenomenon. One of these uses a Monte Carlo approach,[14] while the second is a so-called three-dimensional configuration contamination model.[15] Both of these models predict a substantial increase over the ambient in the concentration in front of vehicle ram surfaces. Collisions between the slower atoms and molecules re-emitted from the surface and the ambient particles result in a reduction of the mean free path in the enhancement region to 16 m in one case and 19 m in another. The scale length of the enhancement is approximately 5 m. In this region, a vast array of collision processes are possible. Poorly understood surface effects enrich the gas-phase mixture with eroded surface materials and act as catalysts for additional processes.

In the case of the Shuttle, the situation is further enhanced and complicated by thruster firings (which not only introduce exhaust materials, but also are bright enough to confuse star trackers and impose high-optical backgrounds on visible photometers[2]) and water dumps (which produce further gas-phase materials and also freeze to form small blizzards). As can be seen from the data shown in Fig. 3, particulates are present in significant numbers in the payload bay. These particulates must add a scattered component and transients to low-light-level data.

Shuttle surface glows measured over a 7 day mission with a portable instrument show no decrease with time.[6] However, the glows associated with the atmosphere explorer satellites increased steadily with time during their several years in orbit when measured relative to the density of atomic oxygen, suggesting a modification of the surface due either to atmospheric collisions or to solar radiation.[16] There are theoretical indications that the glow may become very intense in the infrared.[17,18] These predictions appear to be supported by the ground-based observation of the Shuttle that found the vehicle (and immediate vicinity) to be hundreds of times brighter than the zodiacal light at 1.6 μm.[11] Also, the infrared telescope on the Spacelab 2 mission was saturated in several channels longward of 8 μm for reasons as yet unexplained, but possibly attributable to vehicle halos.

At this time, the extent of vehicle-induced contamination of optical observations from Earth-orbiting platforms is poorly quantified.

While a variety of relevant pieces of information are now available, there is much that we do not conclusively know about the induced environment. We do not know if the spectral detail of the surface glow is the same as that measured by instruments looking away from the vehicle. We do not know how the spectral character of the induced emission depends on such vehicle events as thruster firings, water dumps, or general cleanup of the vehicle due to offgassing. We have only preliminary computations on how the gas concentration around the vehicle may vary with the size and shape of the vehicle. The phenomenon of surface glow or halos surrounding the vehicle represents problems we cannot presently fully explain. Without this understanding, it is not possible to predict the extent of the impact of such effects on a broad class of astronomical, aeronomical, and remote sensing observations planned for Shuttle flights, the Space Telescope, and the Space Station. The reason for this uncertainty is that, to date, insufficient fundamental parameters have been measured to permit an understanding of the atomic and molecular process involved.

Conclusions

To unravel the complexities of the spacecraft/atmosphere interaction glows requires a carefully selected set of mutually related spacecraft-borne instruments that measure the fundamental parameters simultaneously at several locations and times in space. The simultaneity is crucial. The fundamental parameters are the intensity and spectrum of the glows emanating from a variety of surfaces under various known conditions. One could design an optimized experiment to measure sufficient parameters under the same set of conditions to allow solid conclusions to be drawn about the full extent of the phenomenon. A workshop on the Shuttle environment was held in May 1985.[3] Following this workshop, the organizing committee laid out the guidelines for just such an investigation. The primary diagnostic instruments consist of several spectrometers covering the vacuum ultraviolet to the infrared, with a dynamic range adequate for both the very bright near-surface effects and the rather subtle extended halo and other effects. These instruments would be flown in the Shuttle payload bay so as to permit them to monitor sample panels of various surface materials. The panels would be subjected to various angles of attack to the velocity vector. The spectrometers would also be capable of scanning away from these panels in order to survey the near-surface glow scale lengths and the potential vehicle halo. These instruments would be supported by mass spectrometers, and measurements of plasma parameters would be most desirable. Two-dimensional imaging at selected wavelengths would provide additional spatial information as well as revealing particulates. In such an optimized experiment, one would want to be able to control the temperature of the sample panels. Also, because a most important parameter is the dependence of the glows on altitude, it would be desirable to repeat the measurements at various altitudes (e.g., 400-450, 250-300, and 180-200 km). In addition, data would be needed during thruster firings and water dumps, and while such events are specifically inhibited. Deliberate perturbations of the environment in the vicinity of the surfaces under study would be achieved by controlled releases of known gases. (The releases in thruster exhaust are known to enhance surface glows.)

The selection of the panel surface materials is an important issue. One category of surfaces are those typically used in optical instruments: 1) black paint of the type used to coat the baffles of the space telescope (Chemglaze Z306), 2) black anodized aluminum (used extensively within optical instruments, 3) MgF_2 (in this case, deposited on a nonspecular substrate) as a widely used ultraviolet mirror coating, and 4) SiO (also on a nonspecular substrate) as a mirror surface protective coating and also representative of the Shuttle surface material.

The spatial extent (or scale length) of the glow could be determined by moving the panel away from the field of view.

Evidence is unclear as to what role the surface plays in the glow mechanism. Some possibilities are:

1) If facing into the ram direction, the surface may act as a concentrator of gases.

2) Materials with low vapor-pressure oxidation products act as sources of gas.

3) The surface may have catalytic activity for some reactions producing the glowing species or its precursor.

4) The surface may absorb or thermalize gases from another source (e.g., thrusters), which then contribute to the glow.

In order to study the physics and chemistry of the processes involved, other candidates might include: 1) oxidizable materials (carbon, polyethylene, Kapton, paints), 2) nonoxidizables (SiC, A1, Au), and 3) high-surface-area materials (Shuttle tile).

Clearly, even segments of this complete experiment would provide much needed information.

While progress is being made in the development of the fluid dynamical models to describe the passage of a vehicle through the ambient environment in low Earth orbit, much has yet to be done in the overall modeling area. One area of interest would be to take such a fluid dynamics model and fold into it the products of vehicle offgassing, finally generating a predictive spectrum of the induced emissions and their spatial distributions. Work on such a model is currently under way and the preliminary results of the anticipated emissions are published elsewhere.[15]

The study of the glow problems should be facilitated by appropriate laboratory investigations. A considerable effort is presently being invested to establish laboratory neutral beam systems. Several laboratories show promise of achieving atomic oxygen beams representative of the kinetic energy and flux experienced at 250 km Shuttle altitudes (5 eV, 10^{15} $cm^{-2} \cdot s^{-1}$) and usable beams at either lower energy or lower flux are already available. Some systems may not be as well suited for glow studies as others because of the high luminosity of the atom-source region or unknown admixtures of excited states in the beam. Ideally, beam systems should be capable of providing N_2 as well as O at 8 km/s in order to study surface catalytic processes involving nitrogen atoms and oxides of nitrogen.

In summary, the scientific investigations flown on the early Shuttle missions have revealed that the vehicle environment is not entirely what had been expected. Atomic and molecular processes are occurring, for which we cannot presently account and which must be studied from the perspective of their basic science interest. In addition, the environment has the potential to superimpose both striking and subtle signatures on observations made from such space platforms. At this time, we do not have sufficient information on the induced environment from which to fully predict its impact on future science programs.

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The 16 mm pictures of particulates taken on the Spacelab 1 mission were provided by S. Clifton. J. Gregory provided the suggestions of the sample panel surface materials.

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