JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 33, No. 2, March–April 1996

Vehicle Glow Measurements on Space Transportation System Flight 62

G. R. Swenson* and R. L. Rairden†
Lockheed Martin Corporation, Palo Alto, California 94304
D. E. Jennings‡
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
and
M. Ahmadjian§
U.S. Air Force Phillips Laboratory, Hanscom Air Force Base, Massachusetts 01731

Spacecraft glows are primarily a result of satellite surfaces (and their gas clouds) interacting with the rarefied atmosphere in low Earth orbit. Studies of glow were performed in March 1994 on Space Transportation System flight 62 as part of the Office of Astronautics and Space Technology payload objectives. Together, the experimental investigation of spacecraft glow and the spacecraft kinetic infrared test instruments made observations encompassing the far-ultraviolet, ultraviolet, visible, and infrared spectral regions. The experiment included the release of N_2 that was expected to atom exchange with atmospheric O to form surface reactive constituents N and NO. Emission measurements indicate that ground state N_2 at orbital velocities does not atom exchange as previously believed. Another key finding was the lack of N_2 Lyman–Birge–Hopfield emissions in the far ultraviolet. Thruster activity, particularly in low elliptical orbit, is found to cause bright enhancements of OI 5577 and 6300 Å emissions in the Shuttle environment. This investigation studied the effects of altitude, temperature, two paint materials (Z306 black Chemglaze® and A276 white Chemglaze), ram-wake orientation, thruster gas clouds, and thruster effluent surface doping on the glow intensity and spectral character.

Introduction

SPACECRAFT glows have been reported as a result of previous satellite experiments. Several references are available in the literature.[1–13] These citations encompass ram glows generated on satellite surfaces over a wide range of spectral wavelengths, as well as thruster-induced glows. The glows in the infrared on the Space Shuttle Orbiter also include water vapor emissions, believed to be collisionally induced by gas phase water vapor traveling in the vehicle cloud that interacts with the atmosphere. Review papers on the subject of spacecraft glow also have been published.[14–16]

Knowledge of the physical processes and of the atomic-molecular participants has accumulated with the number of experimental observations. A primary objective of the Office of Astronautics and Space Technology (OAST) payload flown in March 1994 on Space Transportation System mission 62 (STS-62) was to add to this knowledge. Included in the orbiter payload were the experimental investigation of spacecraft glow (EISG) instruments and the spacecraft kinetic infrared test (SKIRT) experiment. The purpose of this report is to present some of the new information regarding both surface and gas phase glows acquired by the EISG and SKIRT experiments. Briefly summarized by spectral region, the observations available prior to STS-62 had already revealed the following.

1) Visible: A broad continuum emission (4000–7500 Å) with a peak in the red is seen on the Shuttle orbiter surfaces and on other space vehicles. The glow arises from NO_2 molecules formed in an excited state on these surfaces. NO formation occurs when atmospheric O encounters the vehicle structure at ram velocity and reacts with adsorbed NO. The NO doping may originate from atmospheric NO pickup or from atmospheric N and O combining on the surface. From related information it was also believed that NO could be the result of vehicle cloud N_2 undergoing atom exchange with atmospheric O to produce NO and N, both of which are reactive on surfaces.

2) Far uv: A ram surface normal glow that was spectrally measured as the Lyman–Birge–Hopfield (LBH) bands of the N_2 system in the 1300–2000 Å spectral region has been reported by Conway et al.[3] This glow appeared in the instrument below 250 km altitude and followed a very steep increase with decreasing altitude (roughly proportional to the third power of N_2 density), suggesting a local production of the precursor. Surface recombination of N into excited-state N_2 was a likely source of the LBH emissions. The atom exchange hypothesis described in the previous paragraph was considered to produce the local atomic nitrogen for this recombination.

3) Infrared (IR): Ahmadjian et al.[1] have measured IR signals in the 1–5 μ region identifying NO and NO^+ emissions with an IR circular variable filter spectrometer viewing over a sample facing in the ram velocity direction.

In summary, it was readily apparent before STS-62 that the surface reaction glows associated with optical surfaces and instrument baffles are a result of odd N doping of these surfaces. The residual atmosphere has some of these nitrogen constituents, and if the atmosphere is the exclusive source, then the glow brightness should be a predictable function of altitude and modeling of those constituents available to dope surfaces. The investigation of these early data lead to the hypothesis that atom exchange is important. The ram energy between atmospheric O and vehicle cloud N_2 is slightly greater than required to allow atom exchange, thus NO and N should result. The EISG experiment was designed to release N_2 into the ram atmosphere stream to test this hypothesis.

Gas cloud glows are evident in the tenuous Space Shuttle atmosphere and occur brightly in thruster effluents. One of the major gas glows is the IR emission from atmospheric O colliding with H_2O (Ref. 5). This phenomenon was largely responsible for contaminating the data from the infrared telescope flown on Spacelab 2. Spectral models have now been built that predict the brightness from this interaction to wavelengths of 40 μ (Ref. 17). These glows extend several kilometers in distance from the Space Shuttle as a result of the emission lifetime. The gas glows associated

Received Jan. 18, 1995; revision received Oct. 10, 1995; accepted for publication Oct. 12, 1995.

*Senior Staff Scientist, Palo Alto Research Laboratory, Department 91-20, Building 252, 3251 Hanover Street.

†Research Scientist, Palo Alto Research Laboratory, Department 91-20, Building 252, 3251 Hanover Street.

‡Space Scientist, Organization 693.2.

§Research Chemist, Geophysics Directorate, MC PL/XPG.

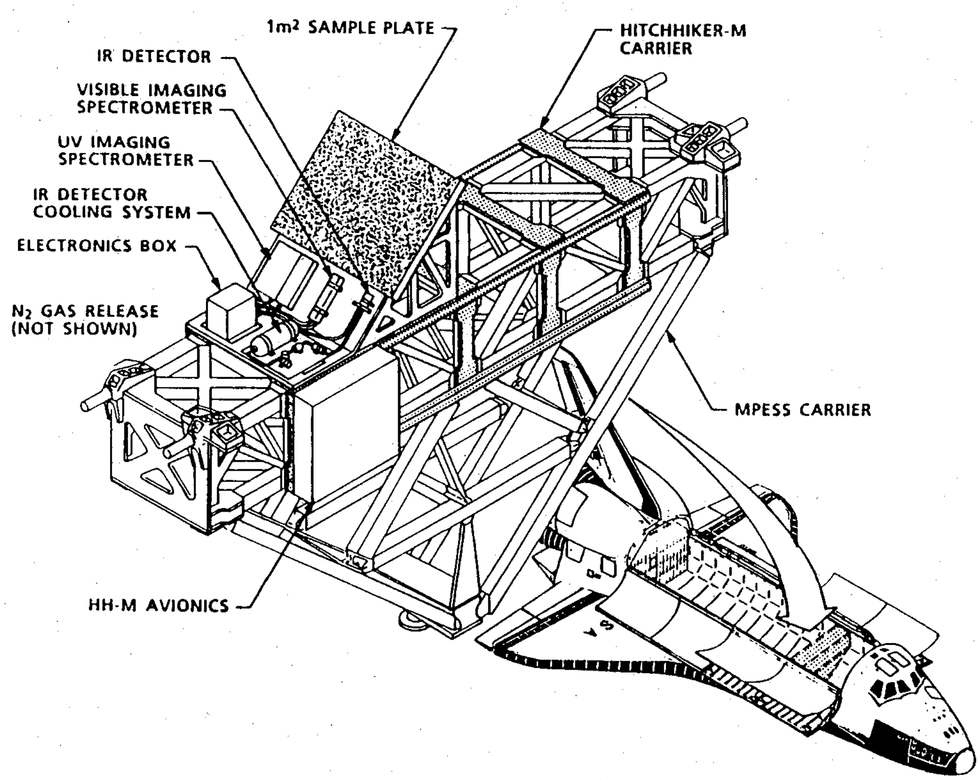

Fig. 1 Schematic diagram including components of the EISG experiment.

with thruster clouds are being studied actively by the U.S. Air Force.[18,19]

The following sections describe the EISG and SKIRT experiments, objectives, and on-orbit operations. The experiment observations regarding surface glows and gas phase glows are then presented.

Mission Objectives

The primary mission objective for the EISG is to develop understanding of the physical processes leading to spacecraft glow phenomena, with emphasis on surface temperature and altitude effects. Optical diagnostics in the far ultraviolet (FUV), visible, and IR spectral regions are used to characterize 1) glow intensity with ram atmosphere and study the variation of cold and warm samples, 2) glow as a function of altitude by studying the altitude effects on the glow sample through stepped circular and elliptical orbits, 3) glow intensity and spectrum as it is modified by the active chemistry of N_2 released into the ram atmosphere, and 4) glow for the two sample paint coatings, Z306 and A276.

The practical motivations for the study of spacecraft glows are to 1) characterize optical instrument backgrounds for NASA payloads; 2) provide guidelines for thermal insulation, material selections, and other engineering considerations to minimize glow effects; and 3) plan flight operations of future experiments that might be adversely affected by glows. Of primary interest are the visible and FUV glows involving the odd N chemistry, and the EISG payload is optimized to study these wavelength regions.

Experiments

The EISG experiment surface is a 1-m square sample plate, half of which is coated with a Z306 Chemglaze® black paint typically used in instrument baffles, and half with a A276 white insulating paint. The paints are deposited on a 250-μ aluminum substrate that is fastened to a 5-cm-thick sheet of rigid foam. Four thermisters are fastened to each sample for temperature monitoring. The volume above the sample was viewed by visible (VIS, 4200–8000 Å) and FUV (1450–3600 Å in 3 steps) spectrometers, an FUV photometer and IR radiometers (1–3 and 3–5 μ channels) to characterize spacecraft glow under a number of conditions. The EISG assembly also contained a nitrogen gas release system to study chemistry with ram atmosphere that was expected to generate glow-producing compounds. A mirror system allowed the spectrometers to view over either of the two materials on the sample plate. The instrument operations were executed by a dedicated onboard computer that received timeline instructions via ground commands. Data were downlinked through a low-rate channel (1200 Bd) and a medium rate data channel (0.5 MHz). Two dedicated tape recorders, with data storage capabilities of 5 h each, were used to buffer data when downlink was not available. In addition, a crew-operated camera/spectrometer system viewed the experiment from an aft flight deck window. A schematic of the EISG instrument payload bay assembly is shown in Fig. 1.

The SKIRT experiment is a cryogenically cooled IR spectrometer dedicated to glow characterization in the 1–5 μ spectral region. SKIRT flow in combination with EISG to obtain IR spectra as part of a comprehensive, multispectral study of the Shuttle glow. The two experiments work together to provide simultaneous observations of glow phenomena. SKIRT had flown previously on STS-39. An InSb detector mounted behind a rotating circular variable filter covers the wavelength range 0.6–5.4 μ with a spectral resolution of 3%. The spectrometer makes repeated scans of 5 s each, or can be commanded to remain at a given wavelength. Also, a radiometer using a HgCdTe detector covers 5.1–5.6 μ. The spectrometer and radiometer use common input optics with a 2×2 deg field of view. The instrument is contained in a solid nitrogen Dewar at an operating temperature of 57 K. A door is opened on orbit to expose the aperture in the vertical direction out of the orbiter bay. A glow plate is mounted adjacent to the aperture as a test surface. This plate is coated with the black telescope baffle paint Chemglaze Z306 that is known to produce a strong glow at visible wavelengths. SKIRT data were directly downlinked during the mission and also stored on an onboard tape recorder as a backup against data-link outages. SKIRT recorded over 40,000 spectra during the STS-62 mission. Additional details of this instrument are described in Ref. 1.

Flight Operations

The experiment flight operations involved the activation of all instrument sequences through an uplink run table that the EISG team manned at the NASA Goddard Space Flight Center (GSFC) hitchhiker payload operations control center. Initial activation of EISG occurred at mission elapsed time (MET) of ~3 h. All functions were verified as operational except those involving high voltage associated with the light intensifiers on the two spectrometers. At MET ~11 h these high voltages were activated. At medium settings the FUV high voltage did not come to a level to observe air glow as expected. This sensor was turned up to full gain just prior to EISG prime operations and performed well. The experiments were allowed to operate during all mission phases as long as the payload resources were available. EISG acquired data from part or all of the night pass of ~100 orbits. Dedicated maneuvers to optimize glow on the sample plate were performed only during EISG prime operations. Much of the mission was flown with the payload bay pointed Earthward and the starboard wing toward ram, which directs the sample plate normal to a 60-deg angle from the ram direction. Data were gathered over the full range of orbit altitudes and over a variety of attitudes during the mission.

The OAST-2 portion of the flight began on day 8 and extended to day 14 of the mission. Seven dedicated operations were planned and executed for the EISG experiment. Orbit inclination was 40 deg. The mission began with a circular orbit of 310-km altitude. On day 9 the orbit was maneuvered to 263 km circular, and on day 11 it was made elliptical, ranging from 263 to 195 km altitude. Orbit and attitude during the EISG prime operations are specified in Table 1. A prime operation for EISG consisted of an orbital night pass (~30 min) with dedicated attitude maneuvers, onboard camera operations, and data downlink. The onboard cameras included an image intensified film spectrometer/imager operated at the aft flight deck window by the mission specialists, and an orbiter black and white low-light video camera. The data collection portion of each prime operation was preceded by a dedicated attitude exposing the EISG sample plate to deep space for the purpose of cooling it. All prime operations ran as scheduled. Data were collected at the 263-km altitude on the first four scheduled EISG prime operations and during 10 additional orbits at that altitude. In the 195-km perigee elliptical orbit of the final mission phase, three prime operations were accomplished, and data were acquired on an additional 10 elliptical orbits. Data were recorded onboard during the final three of these night passes, as the orbiter TDRS antenna had been stowed and medium rate downlink was no longer available.

The low-light-level orbiter cameras were an important part of the glow observations through their ability to provide high time rate images of the visible glow emissions. The original plan was to use a specific orbiter camera located on the forward-starboard bulkhead, but problems developed early in the mission, requiring an alternative. The only other low-light-level camera was the remote manipulator system (RMS) wrist camera, whose use was replanned for EISG prime operations. The viewing perspective was optimized by positioning the RMS camera precisely in the plane of the sample plate. Figure 2 shows this view while the orbiter is still in sunlight. The bulkhead camera anomaly turned out to be fortuitous in that the viewing geometry of the sample plate was significantly improved by using the RMS camera.

Table 1 Summary of EISG prime operations, as flown

Orbit[a]	Attitude	Deadband[b]	Experiment[c]
263 × 263	Bay to ram	Wide	Gas release
263 × 263	+YVV (−10-deg roll) and rolls (5 min/rev)	Narrow	Passive
263 × 263	Bay to ram	Wide	Passive
263 × 263	Bay to ram	Wide	Gas release
263 × 195	Bay to ram	Wide	Gas release
263 × 195	Bay to ram	Wide	Passive
263 × 195	+YVV (−10-deg roll) and rolls (5 min/rev)	Narrow	Passive

[a]Apogee and perigee altitudes, km.
[b]Attitude deadband: wide has infrequent thruster activity and narrow has more frequent thruster activity.
[c]Passive signifies EISG sensors only, no gas releases; gas release signifies gas releases with EISG sensors operative.

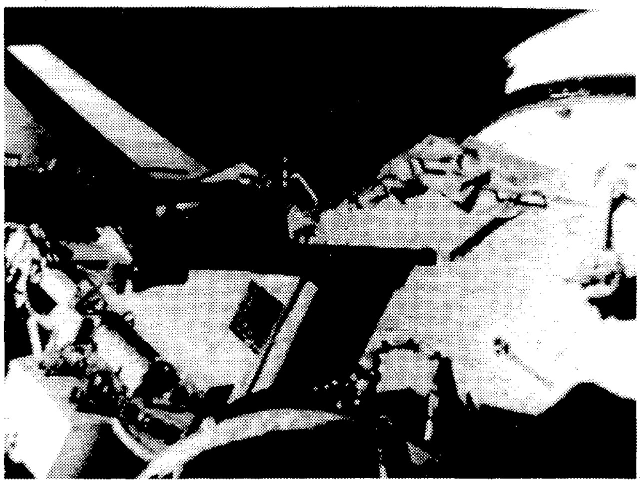

Fig. 2 EISG experiment viewed from the orbiter RMS wrist camera.

Detailed Observations

Gas Release Observations

During the N_2 gas release, the glow was extinguished during release times and reappeared after the release was complete, without enhancement. It is well known that NO (nitric oxide) doped surfaces that are subsequently bombarded by ram O results in NO_2^* and associated emission as the NO_2^* leaves the surface. This process has been validated in ground chamber experiments[20] as well as on STS-39.[9] Some NO is known to be present in Earth's atmosphere, and early theories suggested the atmospheric source was the sole supply of NO. It was later believed that NO could be made chemically by $O + N_2 \Rightarrow NO + N$, where the O is from the ram atmosphere and the N_2 is resident in the spacecraft environment. The minimum energy required to produce this reaction is 3.26 eV. The 8-km/s ram O velocity has a translational energy of ~5 eV that, in collision with N_2, results in a center of mass energy of 3.38 eV. This is slightly greater than the reaction endothermicity. Upschulte et al.[21] measured N_2 atom exchange cross sections of $>10^{-17}$ cm^2 with O at 8 km/s. They found a significant increase in the cross section with increased velocity.

Thruster effluent has been observed to pass in front of vehicle surfaces, and in some cases the effluent is collisionally thick so that the glow is extinguished (temporarily), but then enhanced by several orders of magnitude. We postulate that the $O + N_2 \Rightarrow NO + N$ reaction is responsible for those observations. (See the following subsection, Altitude Effects, for further discussion.)

During the release of N_2 the ram glow was expected to be somewhat diminished (but not extinguished) while the N_2 inhibited the atmospheric O from reaching the sample. The N_2 acts as a collisionally thick barrier to stop the ram atmosphere before it collides with the surface. Modeling of the EISG gas flow rate has shown that it will produce a collisionally thick barrier to ramming O (Ref. 22). As the N_2 gas flow turns off, the NO and N products on the ram side of the release cloud should dope the surfaces, provided they were produced. No sign of this was observed during any of the N_2 releases. The gas release rate was 1.5 l/s STP or $\sim 5 \times 10^{22}$ mol/s. On the ram edge of the release cloud, the column rate of N_2 molecules receiving an encounter with a fast O is simply the O fluence ($v_{sc} \times [O]$) $\approx 1 \times 10^{15}$ mol/s, where $[O] = 1.2 \times 10^9$ cm^{-3} at 260-km altitude,[23] and the spacecraft velocity v_{sc} is ~8 km/s. The EISG spectrometers would have observed surface doping only as the N_2 cloud collapsed between pulses. Given the efficiency of the detector, any number above a threshold of 10^{10} NO_2 mol/s would have been detectable. Thus, the efficiency of producing a surface doped NO (and subsequent recombined NO_2) was less than 10^{-5} per initial ram collision that in turn suggests the cross section is less than 10^{-20} cm^2 for atmospheric molecules colliding with cold ground state N_2. This value is significantly lower than the cross section cited in Ref. 21.

Figure 3 is RMS camera imagery of the sample plate acquired with the N_2 release valve closed and open, showing the extinguishing of the glow. In the VIS, IR, and FUV channels, emissions were

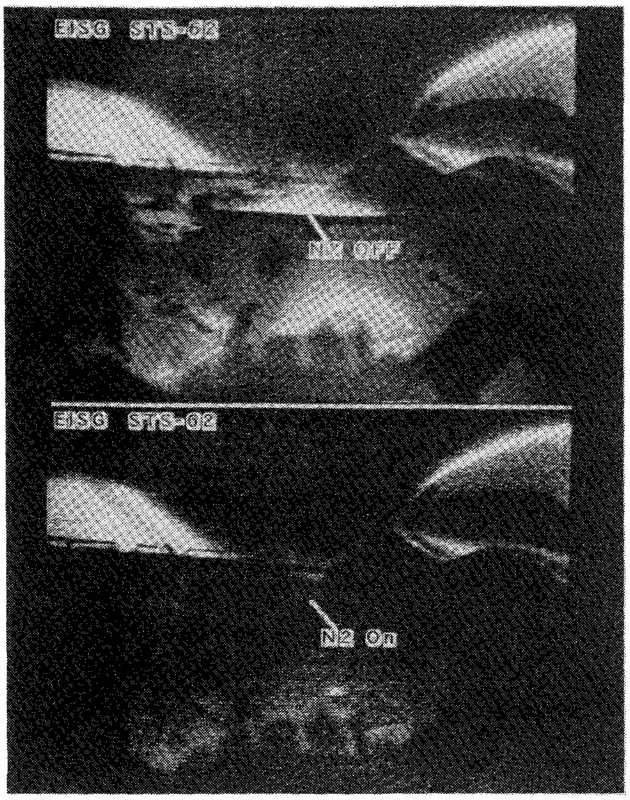

Fig. 3 EISG sample plate: a) spacecraft glows extending from the sample plate and nearby surfaces and b) same scene during an N_2 gas release showing glows extinguished.

either partially or totally extinguished without any enhancement upon return of the glow. The SKIRT experiment verified in the IR that the emissions were extinguished or significantly diminished. Long releases (60 s) and short releases (2 s) were performed. No enhancements were noted in any of the releases. The OAST-2 solar array module plasma interaction experiment (SAMPIE) measured valuable pressure data near the glow instrument during gas releases and during elliptical orbits, which will be very useful in further analyses.

The implications of this result are numerous. It suggests that N_2, as it leaks from cryogenics or life support systems, does not produce an environment that adds to glow production. This form of N_2 does not react with the ram atmosphere to produce a significant amount of odd N products. It further suggests, from a glow standpoint, that the atmosphere (and thruster effluents) are likely the only sources for the odd N glow precursor, at least for the baffle and insulation paint samples flown on STS-62. It also opens up the mystery (which heretofore was felt understood) as to where the N comes from for FUV N_2 LBH glows since atom exchange was the only theory put forth that could support its existence. As will be seen in the later discussions, observations in the FUV help to explain this mystery.

Altitude Effects

It is expected based on earlier passive satellite elliptical data that the visible NO_2 glow follows the atomic oxygen scale height. During the STS-62 mission, data were acquired when the orbiter altitude was circular at ~310 km, followed by circular at ~263 km, and then elliptical between 263- and 195-km altitude.

Visible glow is known to be variable with temperature, ram angle, and altitude. The sample plate was observed to rapidly settle to an equilibrium temperature for a fixed attitude. In the prime EISG bay-to-ram attitude, nose up (i.e., −ZVV, −XLV attitude), this equilibrium temperature was ~−58°C for both halves of the sample plate. The EISG 3 (lower circular orbit) and EISG 6 (elliptical orbit) operations were in this attitude. The glow intensity vs altitude data for EISG 3 and EISG 6 are plotted in Fig. 4, showing the amount of signal increase with decreasing altitude. For EISG 3 and EISG 6, the instrument settings, attitude, and plate temperatures are identical.

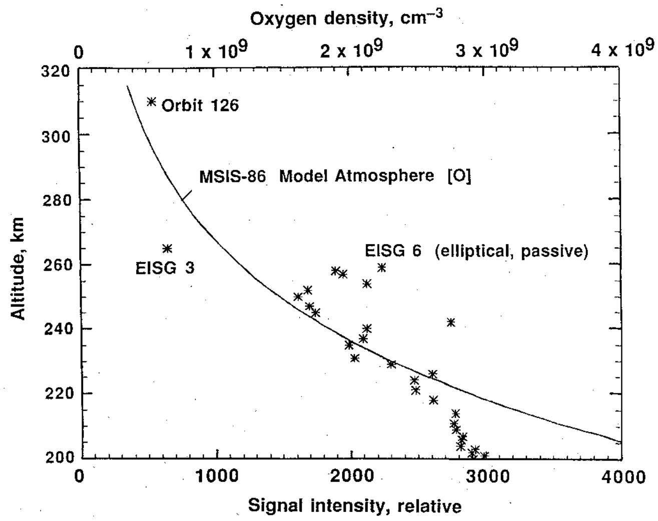

Fig. 4 Relative glow signal vs altitude for EISG 3, EISG 6, and Orbit 126 observations, shown against the MSIS-86 model atomic oxygen density curve.

A data point for the glow intensity from orbit 126 at the 310-km altitude is also plotted. The orbit 126 signal is compensated for instrument gain setting and exposure time, in addition to attitude and temperature conditions. The mass spectrometer incoherent scatter (MSIS)-86 model atmosphere atomic oxygen density curve is overlaid on Fig. 4 with the scale indicated at the top edge of the plot.

The glow brightness in Fig. 4 tends to follow the O-scale height, roughly, but below 220 km it appears to take a slope that does not show the brightening that would be predicted by the continued increase in O density. The authors believe that the large plow cloud densities on the ram side of the large Shuttle vehicle are responsible for impeding energetic O from reaching the surfaces, but this effect is still being studied. The variance in the elliptical data is largely because of enhancements in ram glow caused by thruster effluent surface doping. Near 250 km, for example, the relatively large glow intensities were accompanied by thruster firings and associated heterogeneous chemistry enhancements on the sample plate surfaces.

The low altitude cutoff in glow brightness was not seen on smaller spacecraft. In fact, at lower altitude (below 170 km) the Atmospheric Explorer satellite saw glow in excess of what would be predicted, suggesting a gas cloud or added mechanism to the glow production. On the Shuttle the opposite is seen, and with modeling this emissions shortfall may be explained. It is noted that as 200-km altitude is reached, the glow brightness is more than one-third lower than that which would be expected by following the O density. Above 220 km the brightness does seem to follow the O-scale height.

In the FUV, the N_2 LBH bands were not observed as predicted in the 1450–2000 Å spectral region. During most of the EISG 7 descent toward perigee a bright FUV signal in the 2200–2800 Å region was observed that appears to be thruster-doping related although emission is observed in almost all spectra acquired on that pass. This aspect will be covered in detail with the presentation of thruster-involved glows. The main mystery is how to explain the FUV enhancements of the S3-4 satellite. On S3-4 significant FUV glows were seen at 220 km, brightening to 300 R at 200 km (~STS-62 perigee) and becoming as bright as several kilorayleighs at 170 km. As noted earlier, for some yet unexplained reason the STS-62 visible glow did not brighten much below 220 km and was significantly dimmer than the oxygen-scale height would predict at 200 km. If the neutral plow cloud is stopping glow effects for the visible, it may also be doing the same thing for the FUV processes that were only seen at very low altitudes on the smaller, 1-m class S3-4 satellite. A number of other possibilities exist that require study. The main plausible cause for production of odd N required for the FUV N_2 LBH glows was atom exchange. The EISG gas release proved that the atom exchange does not take place and, furthermore, it is found that in the FUV the N_2 LBH emissions are not observed. These data are self-consistent. The mystery remains to explain the S3-4 satellite observations. (The FUV photometer, which is much

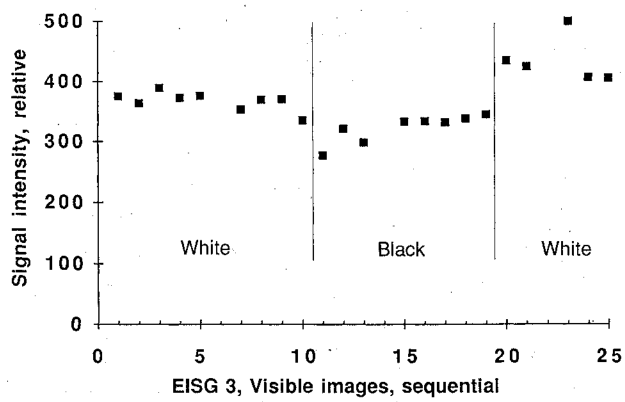

Fig. 5 Visible glow signal of the EISG 3 orbit from the visible spectrometer, 4800–5000 Å spectral region, above the glow sample plate; glow intensity, black paint vs white paint.

more sensitive than the spectrometer, did show a signal during the mission that changed during descent in the elliptical orbits. A survey of the raw signal during the mission shows that this signal has useful altitude information content that is below the sensitivity threshold of the spectrometer.)

Ram NO emissions in the FUV have been predicted for a smaller spacecraft in the 160–100 km altitude region.[24] These emissions are expected to result from exchange reactions. The preliminary findings in these data suggest that most FUV NO emissions occur from thruster dopants, even at low altitude.

Sample Type: Black vs White Paint

Observations of glow above the sample plate were made over each material sample on a number of occasions. Inspection of data from the orbiter camera shows no change in brightness between views across the two material samples.

Sample cycling was performed on EISG 3 (263-km circular orbit, bay to ram attitude) and is presented in Fig. 5. Each spectrum is a 1-min exposure so each data point constitutes a 1-min average sample. Samples begin at orbiter sunset (left) and continue to orbiter sunrise. The first 10 min are observations of the A276 (white) sample, followed by 10 min on the Z306 (black) sample. Both samples have a measured temperature of −58°C during the entire pass. The background for the white sample look direction is toward the Earth, which contributes air glow signals and scattering backgrounds. The plotted points represent wavelength integrated values across the 4800–5000 Å spectral interval in the spectrometer data, where air glow contamination is minimal. The spectrometer shows a slightly brighter signal from the white sample that is attributed here to a slight scattering contribution from Earth backgrounds that are not present in the upward view over the black sample. The orbiter RMS camera viewed both samples against a fixed Shuttle wall background and showed no difference in the two glow signals.

Temperature

Temperatures on the sample plates varied between +13 and −90°C (286–183 K), the extremes of which occurred earlier in the mission and are candidate data for analysis. Often the cold extremes were during attitudes with the experiment plate facing deep space. The sample plates were designed to have a very low thermal capacitance and responded very quickly. A particularly interesting orbit to analyze is orbit 7, where the temperature changed from −25 to −65°C in 15 min.

Both samples followed each other closely in temperature for a period of time at a given attitude. To deduce the temperature effect, the orbital ram angle effect and altitude must be normalized, as well as instrument exposure parameters (gain and exposure time). Data were examined for the prime operations periods where the altitude was constant at 263 km. During most of prime operations the orbiter was in either a bay-to-ram attitude where the temperature on the two samples was from −55 to −65°C, or in a bay-to-Earth attitude where the temperature hovered near −15 to −20°C. As discussed with the material sample signal associated with EISG 3, the glow signal was 350 (with background subtracted) with a gain setting of 8 and an exposure time of 60 s with a temperature of −58°C. EISG 3 was a bay-to-ram attitude, i.e., −XLV, −ZVV. Orbits 185 and 186 were at the same altitude but had a −ZLV, +YVV attitude. The glow signal was 55 (measured vs background) at a temperature of −17°C. To normalize this signal to EISG 3, it must be multiplied by the ram factor (assuming glow intensity follows the cosine of the ram angle, i.e., cos 30/cos 60 = 1.72) and an exposure time factor of two for a total multiplier of 3.44, giving a corrected signal of 190. The ratio of these corrected signals for the measured temperature difference then is 1.89, or an 89% increase in glow intensity for a temperature decrease of 41 K (or a 2.1% per Kelvin gradient). The measurement base used here was selected to avoid contamination from thruster doping that was unavailable information prior to OAST-2. In the earlier assessment of temperature effects[25] the predicted intensity change for these same temperatures would have been a factor of 3.3 vs the 1.89 measured here. This implies a bond energy for NO_2 of 0.075 eV (Ref. 25).

Note that this is a side-viewing measure of intensity at a fixed angle above the sample plate. It was found in earlier laboratory experiments that the projected e-folding distance also shrinks as the molecules move more slowly off the surface.[20] A model needs to be assembled to find the true surface normal intensity as projected from these side-viewing measurements. Using the measurements of Swenson et al.[20] for the temperature change described in the preceding paragraph, a 15% change in the e-folding distance would occur for the temperature change observed here. The bulk of the change must be the result of an increase in the surface saturation of the glow chemistry precursor constituent, NO.

Thruster Effluent

Recent Background

Thruster effluents frequently doped the sample surface. While in ram, doping enhancements were observed in the visible, FUV, and IR wavelengths. (A new publication by Hunton,[26] using STS-4 data from a quadrupole mass spectrometer, shows that NO is increased from thruster firings primarily on orbiter ram surfaces.) The optical effects observed suggest that the NO and N products of the thruster gas are producing these optical enhancements. Viereck et al.[18] have identified and reported HNO product emissions from hand-held camera spectra. The thruster effluent cloud includes $\sim\frac{1}{3}$ mole fraction of H_2O and N_2, significant amounts of CO and H_2, and minor amounts of CO_2, O_2, H, and MMH-NO_3. Although NO and N are not major advertised products of the vernier burn, they are possibly generated as a result of the effluent clouds interacting with the atmosphere or they may be direct products of the burn. One major difference between thruster effluent N_2 and the gas release N_2 is that the thruster effluent N_2 is vibrationally excited, whereas the gas release N_2 is not. A second difference (for ram directed thrust) is the increased velocity difference between thrusted and ram gasses. It is possible that atom exchange is occurring with vibrationally excited N_2 and not with ground state N_2 (as was demonstrated by the N_2 gas release experiment).

Another phenomenon involving gas phase glows associated with thruster effluent is the production of oxygen emissions. Visible oxygen lines at 5577 Å (green) and 6300 Å (red), commonly observed in the Earth's air glow, were also observed to be frequently enhanced in the Shuttle environment. This enhancement was seen in ground-based observations of the Shuttle from Haleakala, Hawaii, for flight STS-41[27] and also in hand-held spectrometer data from the auroral photography experiment.[19] Emissions were especially bright at the elliptical orbit perigees. The ground-based observations saw only the OI 6300 Å (red) emission that extended in a halo several kilometers from the orbiter. This glow appears to be thruster gas cloud related. Thrusters are more active at lower altitudes to keep the orbiter within attitude constraints during elliptical passes. The analysis of STS-62 observations provides a completely new insight into the processes involved.

STS-62 Data

Signals from all instruments are enhanced by the thruster gas and subsequent surface doping of thruster effluent. This section will focus on the heterogeneous reactions on the surfaces observed in the visible and FUV as a result of thruster effluent surface doping. This section does not address the bright glows associated with the burn itself, which is another issue.

The visible glow enhancements on surfaces following thruster firings vary in brightness. The actual brightness depends on the effluent scattering efficiency (i.e., how much effluent reaches the surface for doping) and the ram angle of the surface (for subsequent atmospheric bombardment). Figure 6 is a plot of two typical orbit night passes showing enhancement of the NO_2 continuum for thruster-doping events. Both orbits were circular at ~263-km altitude. The enhanced visible glow associated with thruster activity is indicated in the figure by the arrows. The dc signal level is the ram glow associated with atmospheric pick up of glow reactive species. EISG 2 had active primary reaction control system thruster activity in the first 10 min accounting for the very high glow signal. These are typical of thruster enhancements. Thruster contaminated spectra are excluded from the analyses of temperature effects, ram angle effects, and the dc intensities.

Figure 7 is a spectral plot of the visible glow associated with one of the thruster gas cloud and effluent surface doping events during EISG 7 at 76/12:41:31 UT. The NO_2 continuum is the broadband glow, which has a spectral peak near 6000 Å. The three emission lines are from oxygen atoms emitting at 5577, 6300, and 6364 Å.

The 5577 and 6300 emissions are observed to be highly variable. The 5577 and 6300 have emission lifetimes of 0.74 and 110 s, respectively. The long lifetime for the 6300 suggests why it can extend so far from the Shuttle and be seen from the ground in a big halo, as observed by Broadfoot et al.[27] These emissions are likely produced in gas phase chemistry and not on the surfaces. Figure 8 shows a time history for EISG 6, with signal brightening in the continuum compared with brightening in the OI 5577 and OI 6300. The time axis is horizontal with orbital sunset at left and orbital sunrise at right. Each pixel represents one spectrum, which had a 1-min exposure time. The top panel shows the continuum enhancement in the 4800–5000 Å region of each spectrogram, the middle panel is the signal brightness of the 5577 Å, and the lower panel is the signal brightness of the 6300 Å. Along the line of sight, enhancements are sometimes observed in only one of the spectral lines and sometimes in both. All of the spectral line enhancements are associated with brightening in the continuum. Each EISG orbit shows similar processes. Figure 9 is a time history plot for the same thruster-related phenomenon showing enhancements in the continuum and large enhancements in the 6300- and 5577-Å emissions. Arrows indicate thruster activity. Note the correlation of brightening between the oxygen emissions.

At the middle grating position the FUV channel displayed a sporadic anomalous emission in the descent portion of the EISG 7 elliptical orbit. The sum of several of these spectra is shown in Fig. 10. Superimposed is the spectrum of N recombination (and contamination) glows performed during the calibration of this FUV instrument. The calibration image was acquired from nitrogen afterglow in laboratory tests prior to delivery of the experiment. The primary emission is NO. Note the coalignment of the major band features. The bands in the onorbit spectrum show little rotational structure, which suggests that the NO band system is rotationally hot compared to the laboratory spectrum.

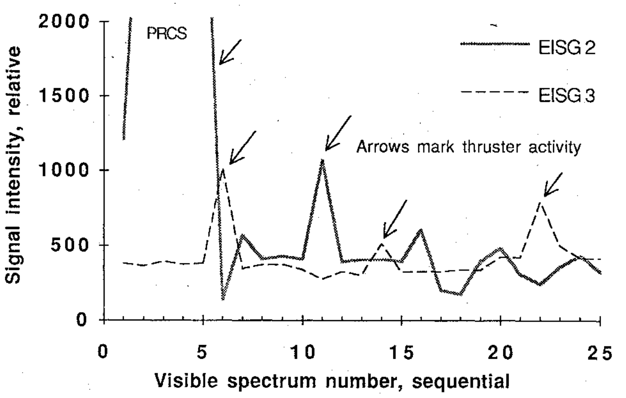

Fig. 6 Visible glow signal over the sample plate vs time during EISG 2 and EISG 3.

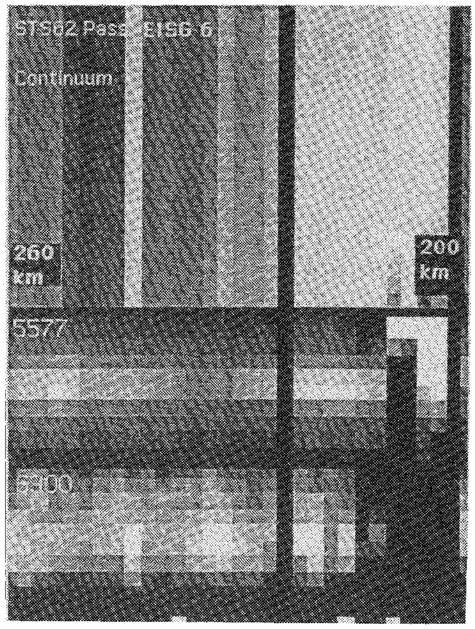

Fig. 8 Time history of spectral features from EISG 6.

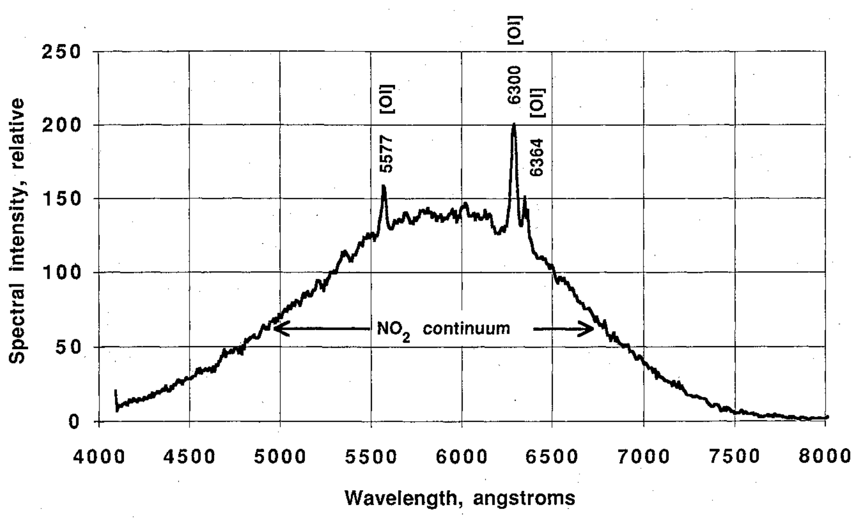

Fig. 7 EISG visible spectrum of thruster enhanced emissions.

Material Effects (Visual), O Fluence

After retrieval of the experiment, physical examination showed extreme erosion and discoloration of the kapton tape used by the integration team to cover cabling, with most erosion on the +Y surface (starboard direction). The O fluence was approximately calculated for the mission using the MSIS-86 model atmosphere.[23] The time durations spent in 310, 263, and 263 × 195 km orbits were computed and total O fluences calculated assuming a surface normal, as shown in Table 2. Note that even though the time spent in elliptical orbit was less than 10% of the mission, $\sim\frac{1}{2}$ of the total mission O fluence was acquired during that elliptical period. Except for the periods of EISG prime operations 5, 6, and 7 (a total of ~3 h), the bulk of the 36 h in elliptical orbit was spent with the +Y (starboard wing) to ram and the bay pointed Earthward. Examination of material erosion and discoloration of the payload showed that most of the surface effects were to those surfaces exposed to the starboard direction.

Material samples have been removed from the payload, and one of the corner brackets was examined for deposition of eroded material. To date, no deposits of evaporated material have been found on surfaces near the black paint.

Visible Spectra Summary

Several visible spectra were taken of phenomena, some of which were related to glow and some not. It became important to sort these spectra to distinguish glow processes from nonglow processes. Normally this sorting task is accomplished with the help of camera images taken along the line of sight (or the visual observations of a crewman) to distinguish the source. In the case of the EISG, the experiment did not include a field-of-view imager along the spectrometer viewing angle. The number of background contaminations encountered was not anticipated. Many of the spectra were acquired viewing down against Earth backgrounds, including Earth air glow, lightning storms, city lights, and sunlight near the terminators. In addition, spacecraft ram glow from atmospheric interactions occurred continuously, depending on the ram angle. Thrusters activated sporadically and data viewing aft over the white sample were often either of the burn itself or the result of surface reactions associated with effluent doping of the surface. The backgrounds that are ever present must be documented and understood so that these effects might be subtracted (or deconvolved) from the composite spectra to obtain, for instance, the intensity of ram glows or doping effects. Figure 11 is a sample spectrum from the Hadamard slit that in effect has 20 times the throughput of the single-slit and for comparison a simultaneous single slit spectrum of the Earth air glow. The atomic air glow lines at 5577, 5896, and 6300 Å and the O_2 atmospheric band system at 7620 Å are superimposed on top of the spacecraft glow continuum that is the NO_2 recombination emission on the sample plate in ram.

Table 2 Atomic oxygen fluence summary[a]

Orbit altitude, km	Time spent, h	Mean [O], cm^{-3}	Fluence, cm^{-2}
310 circular	234	5.6×10^8	3.7×10^{20}
263 circular	51	1.2×10^9	1.8×10^{20}
263 × 195 elliptical	36	4.7×10^9	4.9×10^{20}
Mission total	321	——	1.0×10^{21}

[a]Atomic oxygen density from MSIS 86 model.[23]

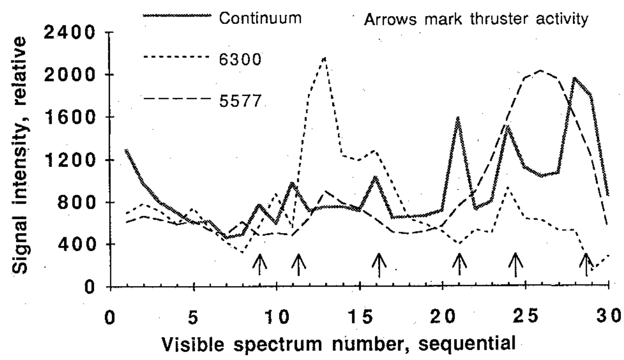

Fig. 9 Time history of the continuum (averaged across 4800–5000 Å) and OI 6300 and 5577 Å emissions.

SKIRT Observations

On four occasions during the mission SKIRT measured the glow during orbiter roll maneuvers. Figure 12 shows spectra from the first roll, during a nightside pass on flight day 1. At this time the orbit altitude was 310 km. The upper trace shows the glow with the bay oriented directly into ram. The lower trace shows the glow at 90 deg from ram. Most of the glow in this region of the spectrum is the result of neutral and ionized nitric oxide (NO, NO^+), with some OH. The glow is greatly enhanced in the ram direction.

Figure 13 compares the glow on day and night sides of a 310-km altitude orbit on flight day 8. The intensity changes by about a factor of 2 in the 4.5-μ NO^+ band and in the 5.3-μ wing of the NO $v = 1\text{–}0$ band. This factor is similar to the ratio of atomic oxygen densities on the day and the night sides at this altitude.

The effect of an EISG nitrogen gas release on the IR glow is shown in Fig. 14. This release took place during flight day 11 at an altitude of 263 km. The neutral nitric oxide (NO) bands at 3.0 and 5.3 μ ($v = 2\text{–}0$ and 1–0) both decreased in intensity by about a factor of 2, and the 4.5-μ NO^+ band decreased by about a factor of 3. Figure 15 shows the 4.5-μ signal during eight 30-s gas-on periods and two 1-min gas-on periods. The glow intensity decreased to the lower level within 0.1 s after each gas release began.

Infrared measurements were made at 310- and 263-km altitude and also during the 263 × 195 km elliptical orbits. The IR intensity was observed to approximately follow the atomic oxygen density with altitude, as expected.

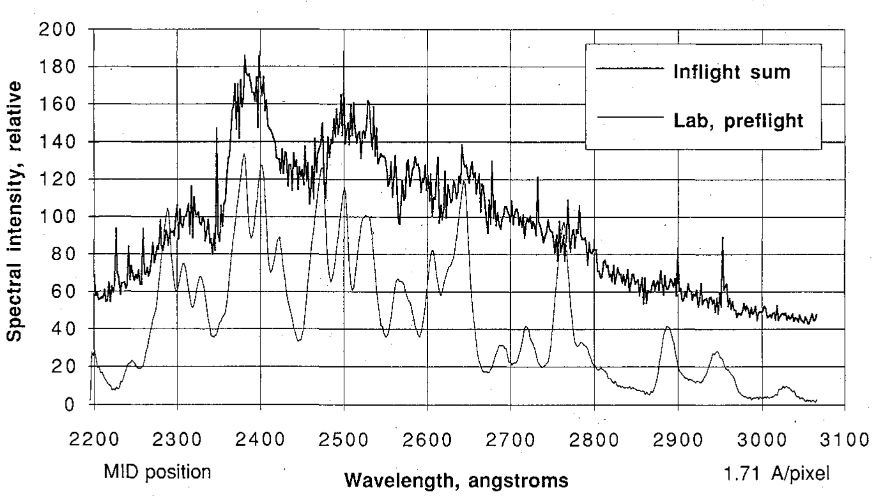

Fig. 10 FUV spectrum of glow associated with thruster effluent doping of the sample plate during EISG 7.

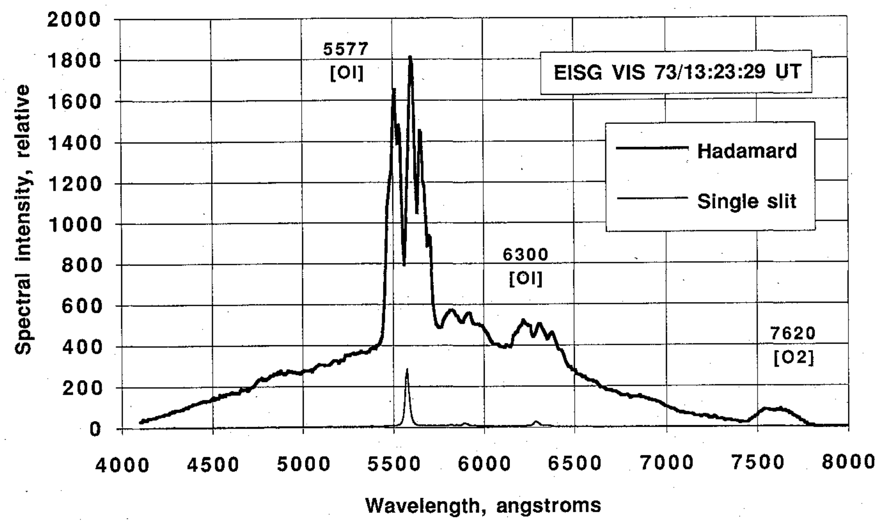

Fig. 11 EISG visible spectrum with the Hadamard slit, viewing toward the Earth air glow.

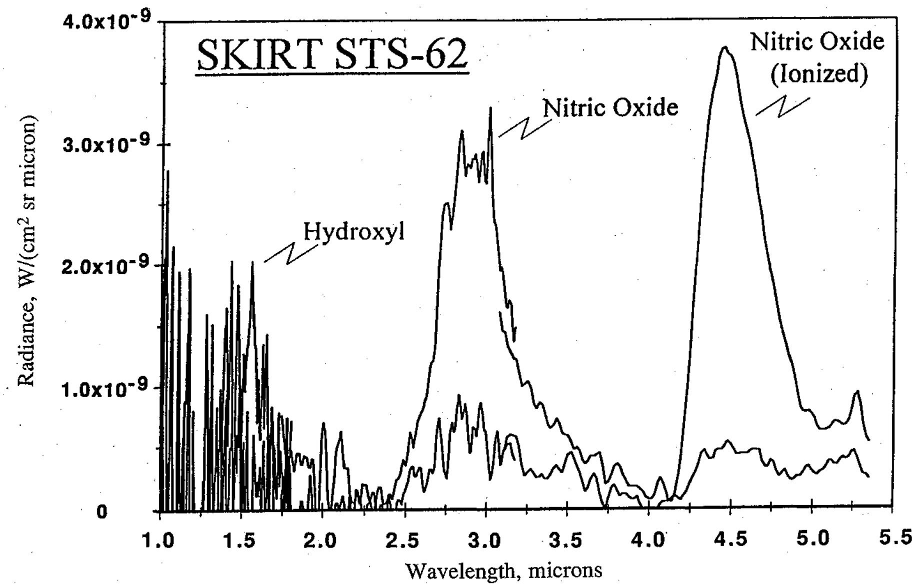

Fig. 12 Spectra from a roll maneuver, measured by the SKIRT instrument.

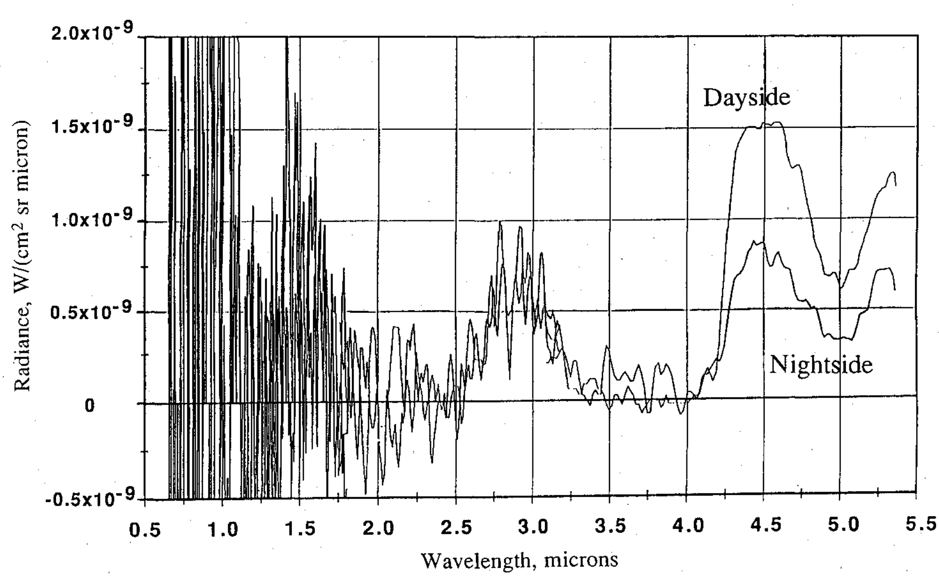

Fig. 13 IR glow measured by SKIRT on the day and night sides of a 310-km orbit.

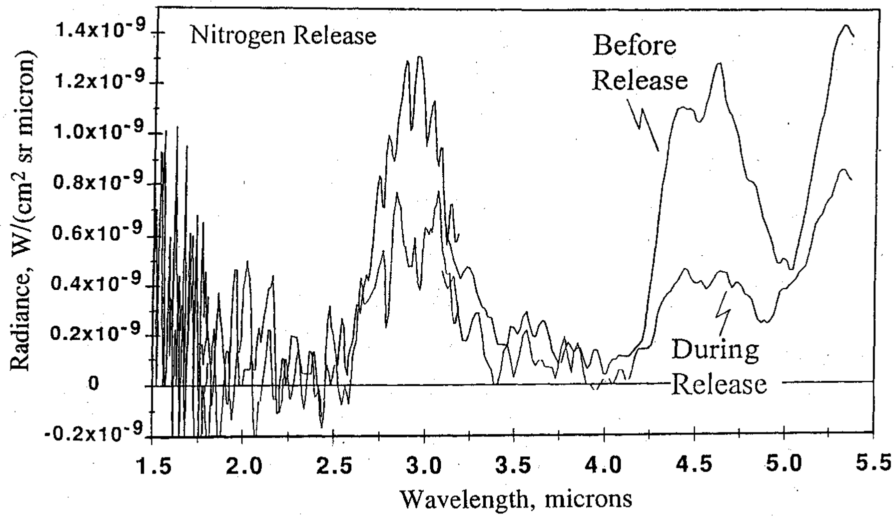

Fig. 14 Effect of EISG nitrogen gas release on the IR glow measured by SKIRT.

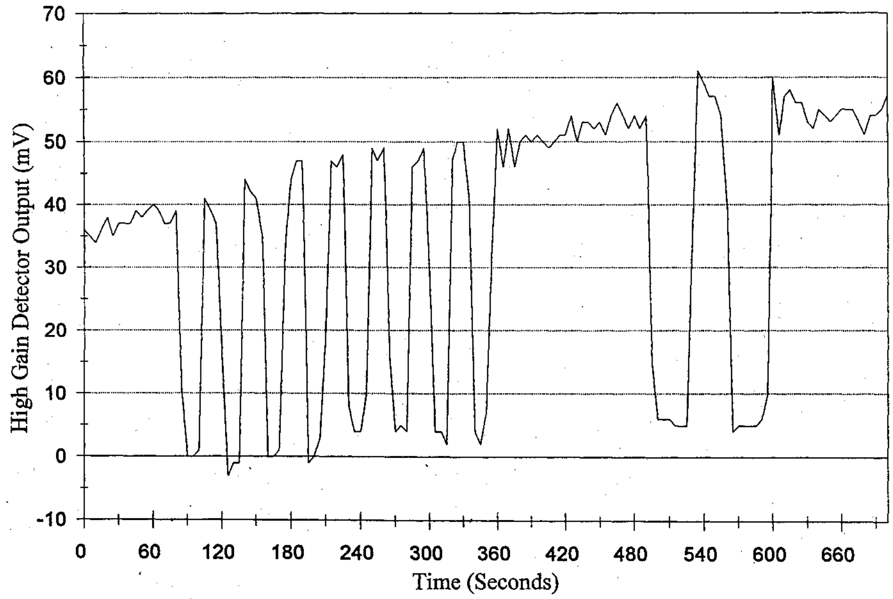

Fig. 15 NO^+ 4.5-μ signal through eight 30-s and two 1-min N_2 releases measured by SKIRT.

Summary

A key finding in the EISG experiment was the fact that N_2 released in the ground state, into the orbiter environment, did not atom exchange with atmospheric O. Atom exchange would have resulted in the production of N and NO, which are surface reactive. Such production did not occur. The outgassing of N_2 from life support systems or as an open source cryogen does not contribute to spacecraft glow. The SKIRT experiment also observed a near total modulation of NO and NO^+ during the N_2 gas release experiments. It has been confirmed here that thruster effluent doping of surfaces does contain large amounts of surface reactive species that lead to emission. NO is ever present in the effluent.[26] N_2 is vibrationally excited in the thruster burn, and the translational energy of ram O well exceeds the threshold of atom exchange as a potential source.

The visible spectrum includes not only the expected NO_2 continuum but also thruster modulated atomic oxygen 5577- and 6300-Å emissions in low elliptical orbit. The glows were bright and extended, often resident for minutes after a release. It has been suggested that this is a result of vernier nozzles sticking open and raw fuel contributing to the occasions of extended enhancements.[22]

The FUV spectrometer did not record significant N_2 LBH emission, though intense NO bands were observed. This lack of significant LBH was an unexpected result.

Acknowledgments

The EISG experiment team was supported by the NASA OAST as part of the INSTEP program under Contract NAS9-18287 through the NASA Johnson Space Flight Center (JSC). NASA OAST also supported the instrument integration. The SKIRT experiment was developed by the U.S. Air Force and was flown originally on STS-39. SKIRT is a result of a joint effort among the U.S. Air Force Phillips Laboratory, NASA GSFC, The Aerospace Corporation, and Mission Research Corporation. The SAMPIE instrument was provided under the direction of NASA Lewis Research Center. The experiment success was because of the dedication of a large number of people, including the STS-62 flight crew, flight operations teams at NASA JSC, and in particular, the OAST-2 program management and integration team at NASA GSFC located in the hitchhiker program offices.

References

[1]Ahmadjian, M., Jennings, D. E., Mumma, M. J., Espenak, F., Rice, C. J., Russell, R. W., and Green, B. D., "Infrared Spectral Measurement of Space Shuttle Glow," *Geophysical Research Letters*, Vol. 19, No. 10, 1992, pp. 989–992.

[2]Banks, P. M., Williamson, P. R., and Raitt, W. J., "Space Shuttle Glow Observations," *Geophysical Research Letters*, Vol. 10, No. 2, 1983, pp. 118–121.

[3]Conway, R. R., Meier, R. R., Strobel, D. F., and Huffman, R. E., "The Far Ultraviolet Vehicle Glow of the S3-4 Satellite," *Geophysical Research Letters*, Vol. 14, No. 6, 1987, pp. 628–631.

[4]Dean, D. A., Huppi, E. R., Smith, D. R., Nadile, R. M., and Zhou, D. K., "Space Shuttle Observations of Collisionally Excited Outgassed Water Vapor," *Geophysical Research Letters*, Vol. 21, No. 7, 1994, pp. 609–612.

[5]Koch, D. G., Fazio, G. G., Hoffmann, W., Melnick, G., Rieke, G., Simpson, J., and Witteborn, F., "Infrared Observations of Contaminants from Shuttle Flight 51-F," *Advances in Space Research*, Vol. 7, No. 5, 1987, pp. 211–221.

[6]Mende, S. B., Garriott, O. K., and Banks, P. M., "Observations of Optical Emissions on STS-4," *Geophysical Research Letters*, Vol. 10, No. 2, 1983, pp. 122–125.

[7]Mende, S. B., Swenson, G. R., Clifton, K. S., Gause, R., Leger, L., and Garriott, O. K., "Space Vehicle Glow Measurements on STS 41-D," *Journal of Spacecraft and Rockets*, Vol. 23, No. 2, 1986, pp. 189–191.

[8]Swenson, G. R., Mende, S. B., and Clifton, K. S., "STS-9 Shuttle Glow: Ram Angle Effect and Absolute Intensities," *Geophysical Research Letters*, Vol. 13, No. 6, 1986, pp. 509–512.

[9]Viereck, R. A., Murad, E., Green, B. D., Joshi, P., Pike, C. P., Heib, R., and Harbaough, G., "Origin of the Shuttle Glow," *Nature*, Vol. 354, Nov. 1991, pp. 48–50.

[10]Viereck, R. A., Mende, S. B., Murad, E., Swenson, G. R., Pike, C. P., Culbertson, F. L., and Springer, R. C., "Spectral Characteristics of Shuttle Glow," *Geophysical Research Letters*, Vol. 19, No. 12, 1992, pp. 1219–1222.

[11]Yee, J.-H., and Abreu, V. J., "Visible Glow Induced by Spacecraft–Environment Interaction," *Geophysical Research Letters*, Vol. 10, No. 2, 1983, pp. 126–129.

[12]Yee, J.-H., Abreu, V. J., and Dalgarno, A., "The Atmosphere Explorer Optical Glow near Perigee Altitudes," *Geophysical Research Letters*, Vol. 12, No. 10, 1986, pp. 651–654.

[13]Zhou, D. K., Pendleton, W. R., Jr., Bingham, G. E., Steed, A. J., and Dean, D. A., "Infrared Spectral Measurements (450–2500 cm^{-1}) of Shuttle-Induced Optical Contamination," *Geophysical Research Letters*, Vol. 21, No. 7, 1994, pp. 613–616.

[14]Green, B. D., Caledonia, G. E., and Wilkerson, T. D., "The Shuttle Environment—Gases, Particles and Glows," *Journal of Spacecraft and Rockets*, Vol. 22, No. 5, 1985, pp. 500–511.

[15]Kofsky, I. L., and Barrett, J. L., "Spacecraft Glows from Surface Catalyzed Reactions," *Planetary and Space Science*, Vol. 34, No. 8, 1986, pp. 665–681.

[16]Mende, S. B., Swenson, G. R., and Llewellyn, E. J., "Ram Glow: Interaction of Space Vehicles with the Natural Atmosphere," *Advances in Space Research*, Vol. 8, No. 1, 1988, pp. 229–241.

[17]Meyerott, R. E., Swenson, G. R., Schweitzer, E. L., and Koch, D. G., "Excitation of the Low Lying Vibrational Levels of H_2O by $O(^3P)$ as Measured on Spacelab 2," *Journal of Geophysical Research*, Vol. 99, No. A9, 1994, pp. 17559–17575.

[18]Viereck, R. A., Bernstein, L. A., Mende, S. B., Murad, E., Swenson, G. R., and Pike, C. P., "Visible Spectra of Thruster Plumes from the Space Shuttle Primary Reaction Control System," *Journal of Spacecraft and Rockets*, Vol. 30, No. 6, 1993, pp. 724–730.

[19]Viereck, R. A., Murad, E., Pike, C. P., Mende, S. B., Swenson, G. R., Elgin, J. B., Bernstein, L. S., and Cucid, S., "$O(^1S)$ 557.7 nm and $O(^1D)$ 630 nm Emissions in Shuttle Thruster Plumes," *Journal of Geophysical Research*, Vol. 100, No. A4, 1995, pp. 5819–5825.

[20]Swenson, G. R., Leone, A., Holtzclaw, K. W., and Caledonia, G. E., "Spatial and Spectral Simulations," *Journal of Geophysical Research*, Vol. 96, No. A5, 1991, pp. 7603–7612.

[21]Upschulte, B. L., Oakes, D. B., Caledonia, G. E., and Blumberg, W. A. M., "Infrared Emissions Arising from the Reactions of Fast O/O^+ with N_2," *Geophysical Research Letters*, Vol. 19, No. 10, 1992, pp. 993–996.

[22]Viereck, R. A., private communication, U.S. Air Force Phillips Lab., Hanscom AFB, MA, Dec. 1994.

[23]Hedin, A., "MSIS-86 Thermospheric Model," *Journal of Geophysical Research*, Vol. 92, No. A5, 1987, pp. 4649–4662.

[24]Karipides, D. P., Boyd, I. D., and Levin, D. A., "Prediction of Ultraviolet Emissions in Rarefied Hypersonic Flow," AIAA Paper 95-2091, June 1995.

[25]Swenson, G. R., Mende, S. B., and Llewellyn, E. J., "The Effect of Temperature on Shuttle Glow," *Nature*, Vol. 323, No. 6088, 1986, pp. 519–522.

[26]Hunton, D. E., "Thruster Firing Effects in the Shuttle Environment, 1. Neutral Gas Composition," *Journal of Geophysical Research*, Vol. 99, No. A3, 1994, pp. 3999–4009.

[27]Broadfoot, A. L., Anderson, E., Sherard, P., Knecht, D. J., Viereck, R. A., Pike, C. P., Murad, E., Elgin, J. E., Bernstein, L. S., Kofsky, I. L., Rall, D. L. A., Blaha, J., and Culbertson, F. L., "Spectrographic Observation at Wavelengths near 630 nm of the Interaction Between the Atmosphere and the Space Shuttle Exhaust," *Journal of Geophysical Research*, Vol. 97, No. A12, 1992, pp. 19501–19508.

I. D. Boyd
Associate Editor