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Analysis of STS-39 Space Shuttle Glow Measurements

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Measurements of Space Shuttle glow were conducted on STS-39. Cargo-bay infrared and visible sensors measured intensities and spectral distributions of shuttle glow as a function of attitude, gas releases, day/night, and mission elapsed time. One of these sensors, the Spacecraft Kinetic Infrared Test (SKIRT), was a cryogenic infrared spectrometer (0.6–5.4 μm) which observed nitric oxide, ionized nitric oxide, and hydroxyl in the quiescent and thruster-enhanced Shuttle glow. A nitric oxide gas release significantly enhanced the glow and showed a fast gas-phase reaction and a slower surface-mediated reaction. The glow was also shown to be dependent on the orientation of the shuttle. The change in glow intensity from pointing the orbiter and sensor along the velocity vector, into ram, versus looking 90 deg from ram, showed a $\cos^2\theta$ dependence. During nonglow quiescent times, when SKIRT was pointed away from ram toward deep space, there were no emissions down to the sensor noise level of 10^{-10} W/cm^2 sr μm. These measurements provided the first infrared measurements with sufficient sensitivity and spectral resolution to identify molecular species associated with Space Shuttle glow. SKIRT demonstrated that very sensitive cryogenic infrared sensors can operate from the Space Shuttle cargo bay.

Nomenclature

h = Planck's constant, erg s
M = third body (reaction surface)
Z = direction normal into the shuttle bay
Δv = change in vibrational quantum number
θ = ram angle, deg
ν = photon frequency, s^{-1}
ν_1 = first vibrational normal mode
ν_2 = second vibrational normal mode

Superscripts

$+$ = positively ionized
$*$ = excited state

Background

SPACE Shuttle and spacecraft observations show that vehicles in low Earth orbits (LEOs) produce a glow effect above surfaces oriented into the direction of motion.[1,2] The first positive confirmation of this glow phenomenon occurred during postflight analysis of visible-light photographs[3] from Space Shuttle mission STS-3, with subsequent confirmation on other shuttle flights.[4] These photographs confirmed earlier spacecraft glow observations on satellites, going back to the 1977 Atmosphere Explorer Satellite program.[5,6] Prior to the STS-39 Spacecraft Kinetic Infrared Test (SKIRT) experiment, no in-flight infrared Space Shuttle glow spectra had been obtained.

Based on the previous orbital observations, Earth-based laboratory experiments, and now these STS-39 data, we know the glow is caused by the kinetic-energy interaction of LEO spacecraft, traveling at approximately 8 km/s, with the high-altitude ambient atmosphere. We also know that the glow produces infrared, visible, and ultraviolet emissions and that both gas-phase and surface-mediated reactions take place.

Figure 1 is a plot of atmospheric neutral-species concentration as a function of altitude (similar plots are available for daytime and nighttime positive-ion concentrations). As can be seen, at 260-km altitude, atomic oxygen is the dominant species, followed by molecular nitrogen.

The concentrations of these neutrals and ions vary not only with altitude and day/night, but also with geographic latitude and longitude, geomagnetic conditions, solar activity, and solar cycle. Thus, the concentrations shown in Fig. 1 are representative, and are not exact numbers for the specific times, altitude, and solar conditions that existed during STS-39. A plausible scenario[7] for the Space Shuttle glow based on the LEO atmospheric composition has impinging nitrogen (N_2) molecules interacting with oxygen (O) atoms in the orbiter plow cloud, producing vibrationally excited nitric oxide (NO) and atomic nitrogen (N). The excited NO radiates in the infrared. The free N combines with N on the spacecraft surface to produce electronically excited N_2^*, which decays by emitting in the ultraviolet. The NO adsorbs on the surface and reacts with impinging O to yield excited nitrogen dioxide (NO_2^*). The decay of NO_2^* produces the characteristic surface visible glow.

Although spacecraft glow has been detected on both Space Shuttles and satellites, the available orbital and laboratory data to validate various glow reaction mechanism hypotheses have been limited for a number of reasons. The execution of an orbital space experiment is a difficult, long-lead, and costly effort. In laboratory experiments the unavailability of fast-atomic-oxygen sources, until recently, pre-

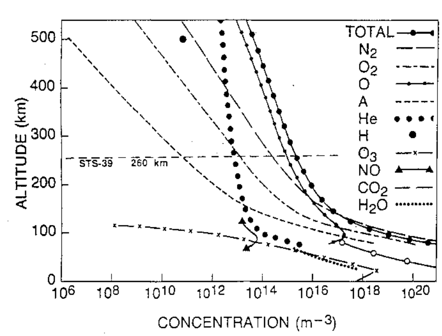

Fig. 1 Plot of atmospheric neutral species as a function of altitude.

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vented ground-based studies of atomic oxygen impacting material surfaces at orbital velocities.

As part of its Department of Defense responsibilities in the design and operation of spacecraft, the U.S. Air Force Geophysics Laboratory (now the Air Force's Phillips Laboratory Geophysics Directorate) allocated funding for on-orbit glow experiments. The purpose was to determine the effects and uses of glow on and for space assets, to understand the chemical and physical processes producing glow, and to determine the level of optical glow contamination in infrared, visible, and ultraviolet (IR/VIS/UV) observations. Areas of interest include IR/VIS/UV glow intensities and spectral distribution as a function of spacecraft materials, spacecraft surface temperatures, vehicle attitude, orbital altitude, day/night atmospheric composition, addition of atmospheric and nonatmospheric precursors into the reaction area, determination of glow mechanisms for both gas-phase and surface-mediated reactions, lifetimes of electronically and vibrationally excited states, and other investigations in support of various applications. In addition, concerns about atomic-oxygen erosion on critical spacecraft surfaces have resulted in increased ground-based investigations with an emphasis on material effects.

The specific objective of the STS-39 SKIRT payload was to obtain the first infrared spectral signature of Space Shuttle glow (including ancillary VIS/UV measurements) with sufficient spectral resolution and sensitivity to identify emitting species and validate proposed reaction mechanisms. Other STS-39 payloads, including the Cryogenic Infrared Radiance Instrumentation for Shuttle (CIRRIS-1A), the Infrared Background Signature Survey (IBSS), and the Arizona Imaging Spectrometer (AIS), were also configured to look at glow.

SKIRT successfully obtained on-orbit measurements of Space Shuttle glow at infrared wavelengths (0.6 to 5.4 μm). Analysis shows spectral band structure consistent with that of NO, NO^+, and hydroxyl (OH). In addition, enhancement of the glow intensity and changes in spectral signatures occurred during thruster firings.

CIRRIS-1A did not definitively observe Space Shuttle glow, but did measure infrared emissions from water contamination associated with the Space Shuttle environment. IBSS did not successfully measure Shuttle glow emissions. Ultraviolet measurements were successfully conducted by AIS, but are not part of this paper.

Photographs taken by the crew during a nitric oxide gas release show an enhanced visible glow effect above the Shuttle surfaces, and these results will be discussed in relation to the SKIRT visible radiometric measurements.

In addition to Space Shuttle glow effects on optical sensors and spacecraft materials, it has long been debated within the NASA and DOD space community whether the gaseous and particulate contamination associated with Space Shuttle environments, or those of any large maneuvering spacecraft, would prevent optimum performance of cryogenic infrared sensors[8] on those vehicles. Arguments have been made that water, nitrogen, and carbon dioxide leaking from the crew compartment, maneuvering thruster by-products, flash-evaporator outputs, water dumps, and outgassing molecules from shuttle tiles and spacecraft surfaces would form and maintain a gaseous and particulate contamination cloud around the vehicle. The gaseous contamination would attenuate incoming optical radiation as well as self-radiate into any onboard sensor's field of view. The particles would scatter solar light and thermally radiate into the field of view (in addition to the optical contamination associated with glow). Because all of these events produce infrared radiation and thermally condensible matter, there were serious concerns expressed in attempting to fly cryogenic infrared sensors sensitive to very low signal intensities onboard the Space Shuttle as well as having sensor components such as telescope baffles and mirrors (at temperatures of approximately 40 K) exposed to this environment. To address these concerns, we operated SKIRT during nonglow times to measure the near-field Shuttle environment to determine short-wavelength infrared and medium-wavelength infrared (SWIR/MWIR) emission levels. Analysis of SKIRT data taken when the orbiter environment was constrained to be as benign as possible (no thruster firings, water dumps, or vehicle vibrations) demonstrates that Space Shuttle contamination levels are acceptable for sensitive cryogenic infrared sensors operating from the Shuttle cargo bay.

Experiment Descriptions

Figure 2 shows the STS-39 cargo-bay configuration. SKIRT and other Hitchhiker payloads occupied the forward part of the cargo bay, IBSS/AIS the middle, and the CIRRIS-1A and associated secondary experiments the aft section.

SKIRT

SKIRT consisted of two separate payloads, designated as SKIRT CVF (circular variable filter) and SKIRT GLOS (gaseous luminosity/optical surfaces). Together with other experiments, avionics, and payload support structures, the Hitchhiker payload was designated as STP-1 on the STS-39 manifest.

SKIRT CVF featured an infrared CVF spectrometer and a long-wavelength infrared radiometer, both sharing common collecting optics and cooled with solid nitrogen. The spectrometer (using an In:Sb detector) covered the wavelength region from 0.6 to 5.4 μm at 2% spectral resolution and conducted a complete spectral scan in

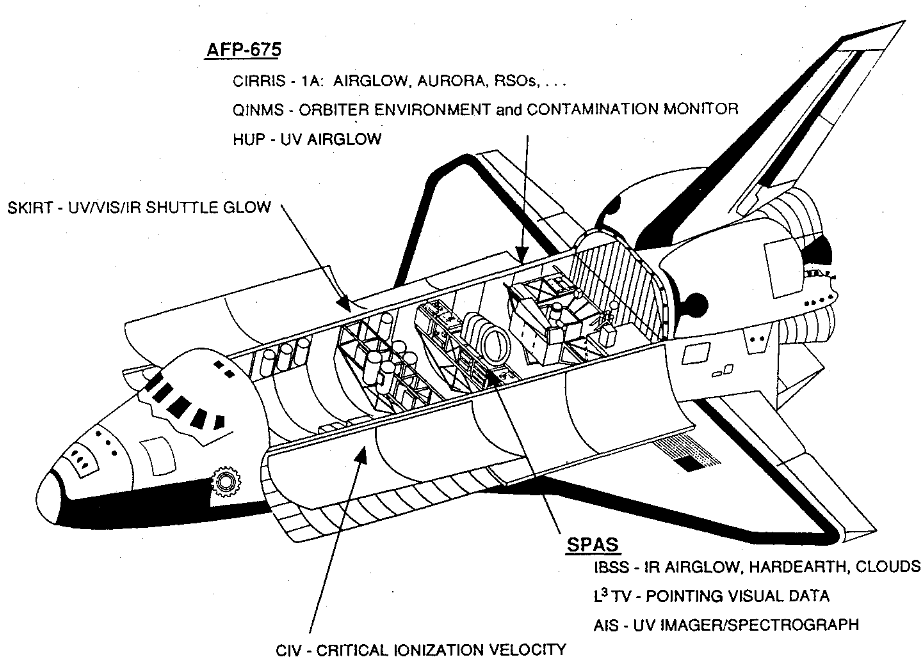

Fig. 2 STS-39 Space Shuttle Discovery cargo-bay configuration.

5 s. The radiometer had a Hg:Cd:Te detector and sampled a single wavelength interval (9.9 to 10.4 μm), which is an atmospheric transmission window for infrared sensors. The detector and optics were cooled to approximately 57 K. An aperture cover was opened on orbit to expose the 2×2 deg field of view along a line of sight directed perpendicularly to the shuttle cargo bay ($-Z$ axis). A detailed experiment description has been previously published.[9]

The SKIRT GLOS sensors were designed for radiometric measurements in the infrared, visible, and ultraviolet wavelength regions. The design philosophy for the infrared modules was that they would be backup payloads to the SKIRT infrared CVF spectrometer. The SKIRT CVF was considered high-risk, with a solid-nitrogen cooling system (never flown before), a stepper-motor-driven filter wheel mechanism, and a motor-driven aperture cover, which had to operate in microgravity, in high vacuum, and over a broad temperature range. SKIRT GLOS, with previously flight-qualified cryocoolers and solid-state components, was considered, in the space business, to be a more reliable assembly.

CIRRIS-1A

The CIRRIS-1A was a U.S. Air Force experiment designed to obtain simultaneous infrared spectral and spatial measurements of airglow, aurora, and targets of opportunity. The primary sensors consisted of a Michelson interferometer (Fourier transform infrared [FTIR]) for high-resolution spectral measurements, and a dual-focal-plane radiometer with selectable bandpass filters for spatial clutter measurements in the 2.5- to 25-μm wavelength region. The interferometer and radiometers shared the collection optics of a highly baffled telescope for simultaneous spectral and spatial measurements within the same field of view. The sensor detectors and optics were cooled to liquid-helium temperatures, 12–40 K, to allow measurements of emissions from weak infrared sources in the 60- to 150-km-altitude atmosphere. A detailed description has been published previously.[10]

The CIRRIS-1A interferometer had a 1-cm^{-1} spectral resolution capability, compared to the SKIRT CVF 40-cm^{-1} resolution at 5 μm, and offered the prospect of actually measuring the rotational line structure associated with the vibrational band structure. This would have provided the definitive measurement of infrared Space Shuttle glow emissions.

At 5 μm the sensitivity of CIRRIS-1A # 2 interferometer detector was approximately 8×10^{-9} W/cm^2 sr μm. The sensitivity of the SKIRT CVF at 5 μm was 1.3×10^{-10} W/cm^2 sr μm. CIRRIS-1A with its As:Si detectors was designed for maximum sensitivity in the long-wavelength infrared (LWIR) and not the SWIR/MWIR region, which overlaped the SKIRT CVF wavelength coverage. As can be seen, SKIRT CVF was more sensitive in the SWIR/MWIR by more than a factor of 10 for near-field extended-source emissions than the CIRRIS-1A.

Even though CIRRIS-1A was not designed for Shuttle glow measurements, on-orbit operations were modified to attempt a glow measurement. Unfortunately, the gimbal system did not have sufficient pitch capability to point the sensor in the vicinity of the orbiter vertical stabilizer and OMS pods, where intense visible glow emissions are known to occur over long optical path lengths when these surfaces are exposed to ram. In addition, because of primary-mirror cleanliness considerations and postflight optical engineering evaluations, the telescope aperture could not be pointed into the ram direction. The only other option was to maneuver the Shuttle remote manipulator system (RMS), i.e., the arm, into the vicinity of the sensor and attempt to measure the glow from a small section of the RMS while it was exposed to ram.

IBSS/AIS

This set of instruments consisted primarily of a helium-cooled grating infrared spectrometer (IBSS), a UV spectrometer (AIS), and low-light-level televisions. The primary mission was to measure the spectral and spatial structure of rocket firings and chemical releases in space. A secondary objective was to measure Space Shuttle glow while the payload was attached to the RMS and pointed by the crew at the vertical stabilizer and OMS pod areas and while those surfaces were exposed to ram.

IBSS did not measure glow. The belief is that it was pointed so close to the shuttle surfaces that the orbiter blackbody thermal emissions swamped out any glow signal. The data, as well as the CIRRIS-1A, would have provided very high-spectral-resolution spectra of glow in the 2.5- to 25-μm region. Unfortunately, this sensor also was not designed with glow as a primary objective, and, like CIRRIS-1A, was operated on a best-effort basis. AIS did measure glow in the UV; however, these data are not part of this paper.

Critical Ionization Velocity Experiment

Also associated with the IBSS/AIS experiment was a gas-release payload, mounted on the forward port cargo-bay sill of Discovery, which discharged small amounts of gases into space to test a critical-ionization-velocity theory. One of these gases was NO, and the results of that gas release will be discussed in the Results and Discussion section.

Flight Operations

The Space Shuttle Discovery (OV-103) and its seven-man crew were placed into a 260-km circular orbit at an inclination of 57 deg on April 28, 1991. Once on orbit, the crew opened Discovery's payload bay doors, enabled power to the payload electrical bus, and configured the Hitchhiker-G avionics for ground control. Continuous 24-h operations were conducted during the 8-day mission.

SKIRT was commanded "on" and continued to operate for 7 days and 22 h. A number of glow measurements were conducted at specific times during the mission when the orbiter attitude was oriented so that the SKIRT payload and surrounding surfaces were exposed directly to ram and away from ram. During non-glow-related times, other measurements were conducted throughout the flight. Over 14,000 spectra of shuttle glows, airglows, auroras, calibrations, and the orbiter environment were recorded. These data provide not only the first infrared measurement of Space Shuttle glow, but also a detailed record of the on-orbit environment associated with large spacecraft structures.

Because of the higher-priority Earth-limb objectives, the CIRRIS-1A dedicated glow measurement was conducted as one of the final CIRRIS-1A observations, and there was only one opportunity allowed in the timeline. To maximize the purity of the Shuttle-glow observation, the measurement was conducted in umbra to prevent direct and scattered solar radiation from entering the CIRRIS-1A telescope. To prevent earthshine and Earth-limb radiation from entering the telescope, the CIRRIS-1A was pointed to deep space. The cargo-bay lights were turned off. The RMS was positioned so that it was 2m above the aperture and 1m to port. The orbiter was flown such that the starboard wing was into the velocity vector and the RMS surface closest to the CIRRIS-1A field of view was exposed to ram. All maneuvering thrusters and contamination events were inhibited to prevent mirror and data contamination. The payload specialist used the CIRRIS-1A joystick gimbal controller to roll the sensor toward the RMS until the detector signal was saturated by the RMS blackbody emission. He then rolled the sensor to starboard until the signal was no longer in saturation. It was hoped at this point the CIRRIS-1A would be measuring glow off the RMS.

Results and Discussion

This section addresses the SKIRT CVF data for quiescent glow, thruster-enhanced glow, comparison with synthetic spectra, day/night glow variations, ram-angle dependence of glow intensities, and contamination-free infrared sensitivity levels. SKIRT GLOS results will be shown for the NO gas release. A discussion of CIRRIS-1A is also included.

Figure 3 is a spectrum of daytime Space Shuttle glow measured when the orbiter was flying bay to ram in a vehicle attitude such that the SKIRT CVF sensor field of view was between 3 and 40 deg from the velocity vector (sensor pointing into ram while looking above the horizon). These scans were acquired after Discovery had been on orbit for over 160 h. The orbiter surfaces (top and bottom) had been heated by the sun during the first day on orbit to bake out water and other adsorbed molecules. By the time these data were collected, outgassing from external surfaces is believed to have been

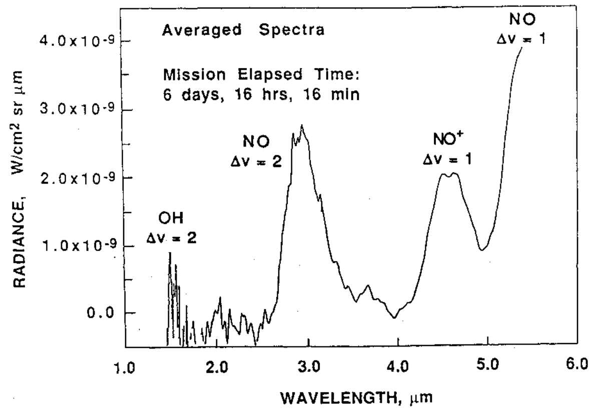

Fig. 3 Infrared spectrum of quiescent Space Shuttle glow (local time 1304 through 1345 h).

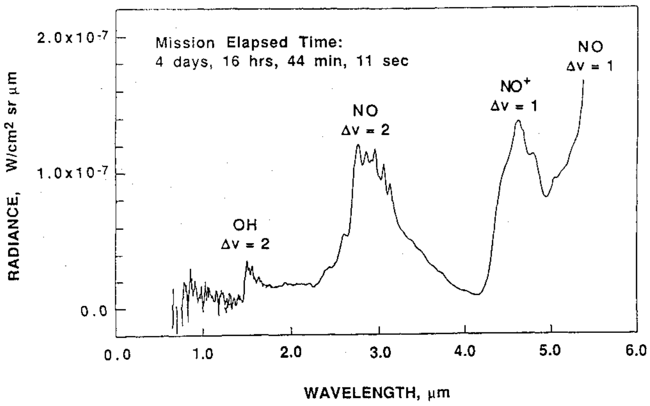

Fig. 4 Infrared spectrum of thruster-enhanced Space Shuttle glow.

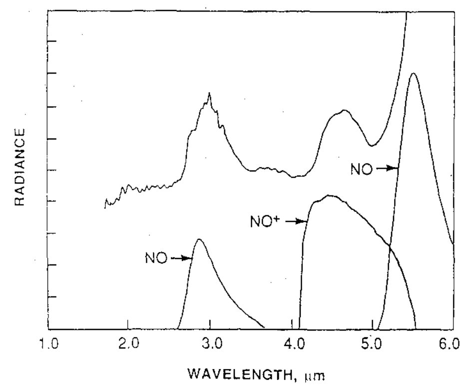

Fig. 5 Comparison of atmospheric NO and NO+ spectra with quiescent Shuttle glow.

minimized. Prior to and during this measurement time, all thruster firings, water dumps, flash evaporators, and other contamination-generating activities were suppressed. Thus, Fig. 3 is representative of the radiance induced by the ambient environment surrounding quiescent LEO spacecraft. Emission features for this "quiescent" glow have been assigned as follows:

λ, μm	Species	Δv
5.3	NO	1
2.9	NO	2
4.5	NO^+	1
1.5	OH	2

Figure 4 is a glow spectrum taken during an orbiter thruster firing with a ram angle of 24.6 deg. A comparison between Figs. 3 and 4 shows that the quiescent glow spectra and thruster glow spectra, although similar in overall appearance, are different both in signal intensity and in spectral content. During quiescent ram conditions the Shuttle glow radiances are on the order of 10^{-9} W/cm^2 sr μm.

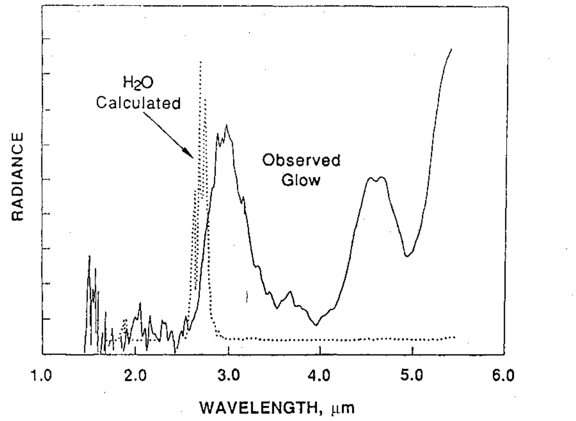

Fig. 6 Comparison of SWIR atmospheric water spectrum with quiescent Shuttle glow spectrum. Dotted line is H_2O at 20-cm^{-1} resolution.

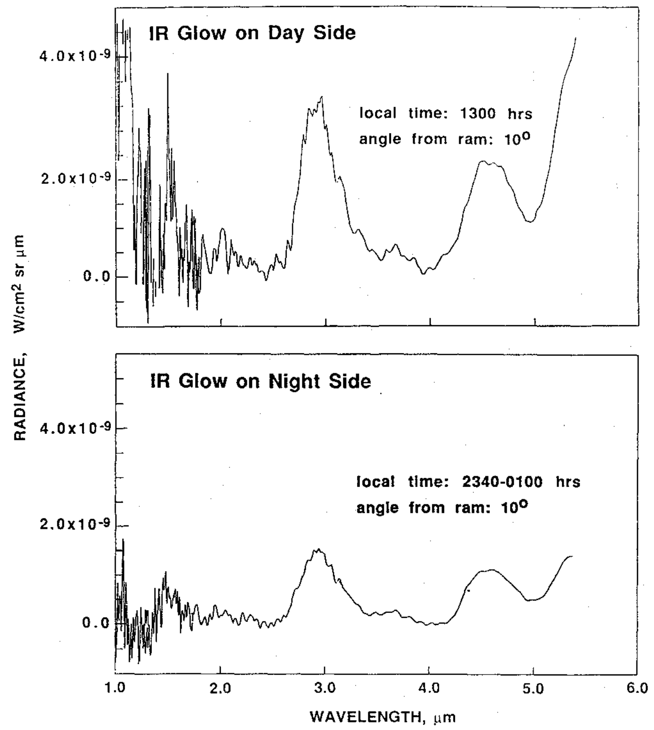

Fig. 7 Daytime vs nighttime Shuttle glow.

During thruster firings the signal intensities increased up to 10^{-7} W/cm^2 sr μm.

The enhanced thruster glow intensity is consistent with visual observations and is caused by the increased concentration of reaction precursors from the thruster exhaust available for reaction with the ambient atmospheric O and N_2. The thruster glow spectrum appears to contain at least NO, NO^+, and OH. To assist in the SKIRT data analysis, synthetic spectra have been calculated using the SHARC[11] atmospheric radiance model. A synthetic spectrum for vibrationally excited NO was generated that closely matches the SKIRT CVF spectral distribution at 2.9 and 5.3 μm (Fig. 5). The 5.3-μm band is assigned to the $\Delta v = 1$ fundamental, and the 2.9-μm band is assigned to the $\Delta v = 2$ overtone. The $\Delta v = 3$ band may be barely visible at 2.0 μm.

In the 2.7-μm spectral region water is also a radiator, and it is known from previous Space Shuttle mass-spectrometer measurements that water is part of the Shuttle environment. To distinguish between the NO overtone and the H_2O $\nu_1 + \nu_2$ combination bands, an atmospheric water spectrum was compared with the quiescent Shuttle glow data (Fig. 6). The peak of the water band is blue-shifted relative to the glow emission. However, there is some overlap with the thruster-enhanced glow data in this spectral region, and water cannot be ruled out as a component of nonquiescent infrared emissions under certain conditions. Similar synthetic spectra were produced for NO^+, and Fig. 5 shows the comparison of a quiescent Shuttle glow spectrum with the spectral distribution for NO^+.

In addition to changes in Shuttle glow caused by thruster firings, there are other factors that may influence the intensities and spectral distributions of the infrared glow. Among these are day/night and ram-angle variations. Since the glow is known to be dependent on atmospheric composition, a diurnal variation in the glow would be expected. Figure 7 compares a daytime glow spectrum with a nighttime glow spectrum. Even though the spectral features are similar, the overall intensity of the nighttime spectrum is down by a factor of approximately 2.5. Both measurements were conducted at a 10-deg angle from ram. These results are consistent with a nighttime decrease of O when atomic oxygen combines with ozone to produce molecular oxygen, and to a decrease in O^+ relative to daytime concentrations.

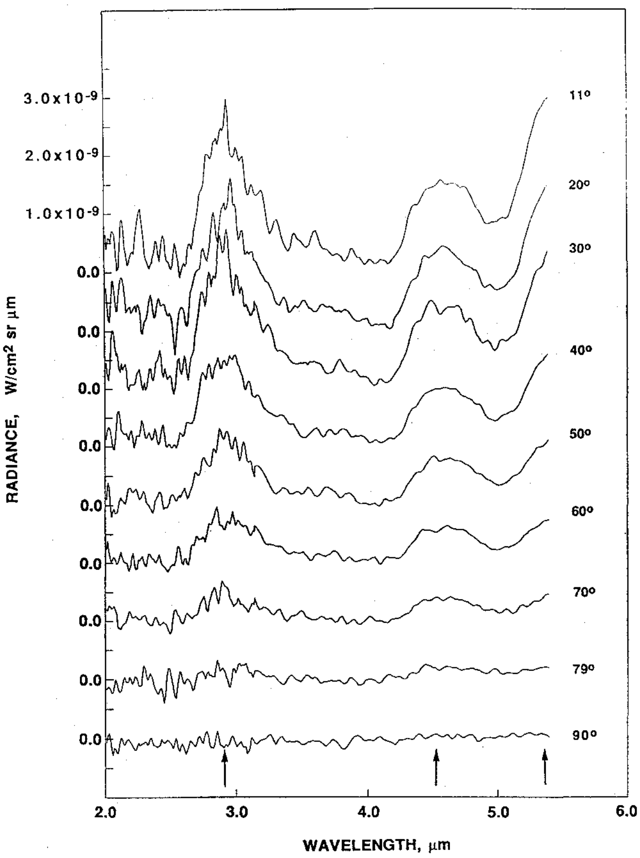

Fig. 8 Variation of quiescent Shuttle glow with ram angle.

From visible observations, it is well known that the glow intensity depends on the ram angle. To measure the effect in the infrared, the Shuttle cargo-bay ram angle θ was varied from 11 to 90 deg. At 11 deg the SKIRT sensor and surrounding payload and Shuttle surfaces were almost directly in ram and exhibited nearly maximum glow intensities. As the ram angles increased and the 8-km/s-velocity spacecraft surfaces were less exposed to the impacting atmosphere, the glow intensity decreased. The variations of the spectral glow emissions with ram angle are shown in Fig. 8. As the surface area near the sensor field of view is exposed less to the incoming atmosphere, the infrared glow emissions weaken; this is consistent with visible-light observations. Since NO appears to be the dominant radiating species in the infrared glow, its 5.3-μm intensity was plotted as a function of ram angle. Figure 9 is a plot of this measurement and shows a $\cos^2 \theta$ fit to the data. In addition, the intensities versus ram angle for 2.9, 4.5, and 5.3 μm were plotted (Fig. 10). Again a $\cos^2 \theta$ fit is observed. This dependence is interpreted as due to a combination of change in the shuttle ram-angle exposure and column depth being viewed. For example, the densities of the incoming O and N_2 would be expected to have roughly cosine dependences on ram angle. A reaction that goes as the product of the densities of these two species would have a $\cos^2 \theta$ dependence on ram angle. Although the match to $\cos^2 \theta$ is quite good, we do not expect this dependence to hold in detail—some faint glow is likely to be present in the wake beyond 90 deg.

During nonglow measurements when the orbiter environment was constrained to be as benign as possible, SKIRT was able to measure down to its noise level of 10^{-10} W/cm^2 sr μm. There are no observable spectral features.

The CIV experiment on STS-39 involved controlled releases of four gases (nitric oxide, xenon, neon, and carbon dioxide). During the NO gas release the SKIRT GLOS radiometers obtained excellent data before, during, and after the event.

Figure 11 is a plot of the visible radiometer signal intensity versus time. At the start of the release there is a rapid increase in signal. The signal stays fairly constant and when the gas is shut off, the signal returns to its baseline level. The return to baseline is a two-stage process. When the plot is expanded on the time axis, there appears a fast decay followed by a slower decay prior to reaching the baseline intensity. This is consistent with Space Shuttle glow being both a short-lived gas-phase reaction and a slower surface-mediated reaction. Figure 12 is a photograph taken by the crew from the aft flight deck window during the event, showing the gas-phase and surface glows. The gas glows brightly in the cargo bay and also creates an enhanced surface glow on the orbiter rear vertical stabilizer, OMS pods, and top port wing.

Based on the SKIRT data and analysis of visible-light photographs,[12,13] it appears that at least two types of reactions are occurring. One is a gas-phase reaction involving nitric oxide and atomic oxygen ($NO + O \rightarrow NO_2^*$), and the other is a surface-

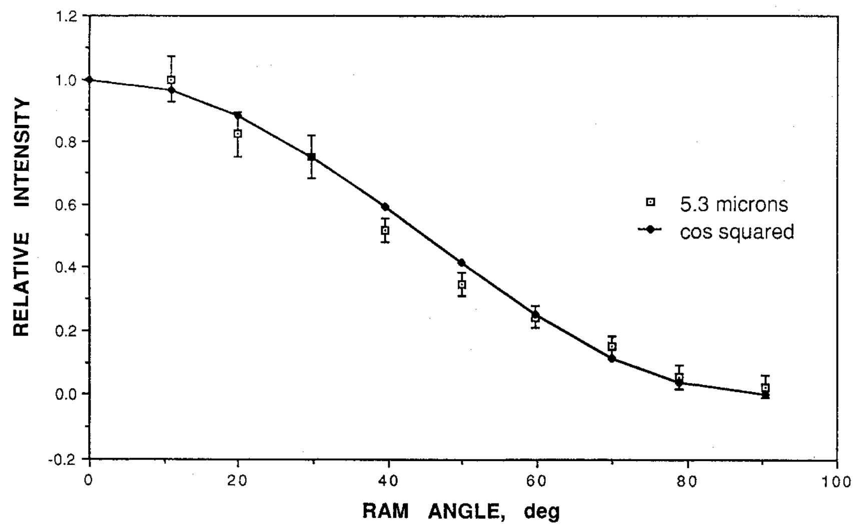

Fig. 9 5.3-μm glow intensity vs ram angle.

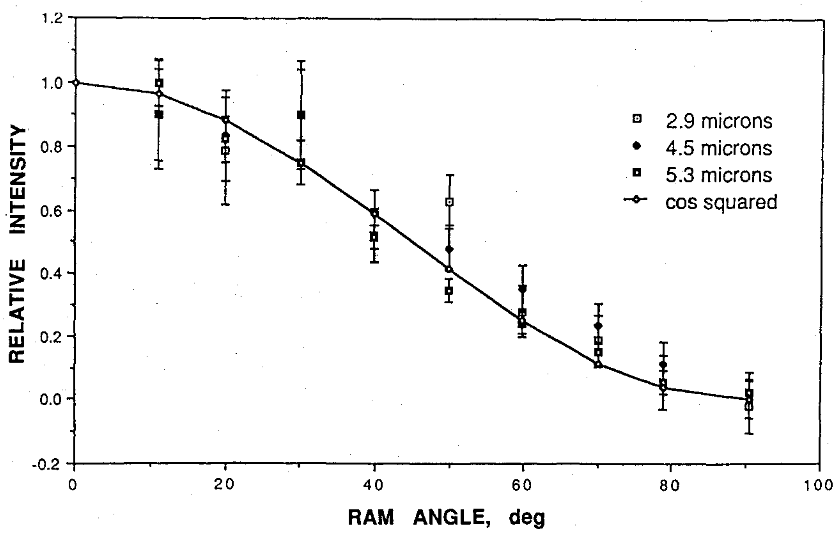

Fig. 10 2.9-, 4.5-, and 5.3-μm glow intensity vs ram angle.

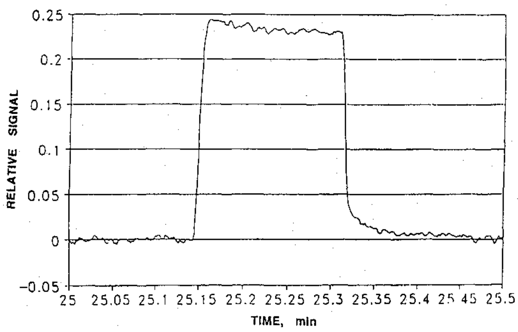

Fig. 11 SKIRT GLOS visible-light radiometer signal during NO gas release.

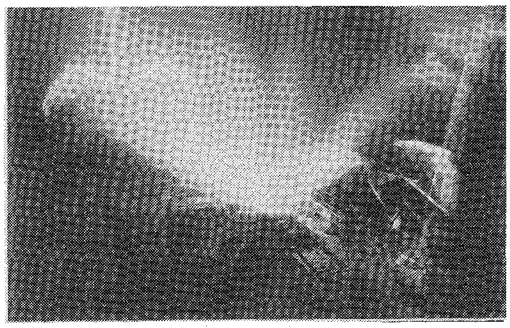

Fig. 12 Photograph taken from Shuttle aft flight deck of NO gas release.

mediated reaction caused by the migration of NO to the vehicle surfaces and subsequent reaction with incoming atomic oxygen to form NO_2^* ($NO + O + M \rightarrow NO_2^*$). Both reactions are followed by excited nitrogen dioxide going to its ground state ($NO_2^* \rightarrow NO_2 + h\nu$).

Although the SKIRT CVF did not observe during the NO gas release, time-evolution measurements were made of thruster firings in the infrared (Fig. 13). The CVF was fixed in position at 4.5 μm and recorded the intensity at this wavelength during the event. The change in thruster glow intensity is quite abrupt—within 0.1 s when a thruster is fired or turned off—supporting the idea that the infrared glow involves gas-phase reactions.

CIRRIS-1A did not detect the spectral emissions observed by SKIRT. We believe that the interferometer did not have sufficient SWIR/MWIR responsivity to see quiescent glow as produced by the small section of the RMS exposed to ram. Had the column density, i.e., optical path length, within the CIRRIS-1A field of view been greater, the glow might have been measured with the sensor's 1-cm^{-1} spectral resolution capability. However, shuttle water contamination was observed during CIRRIS-1A Earth-limb measurements when

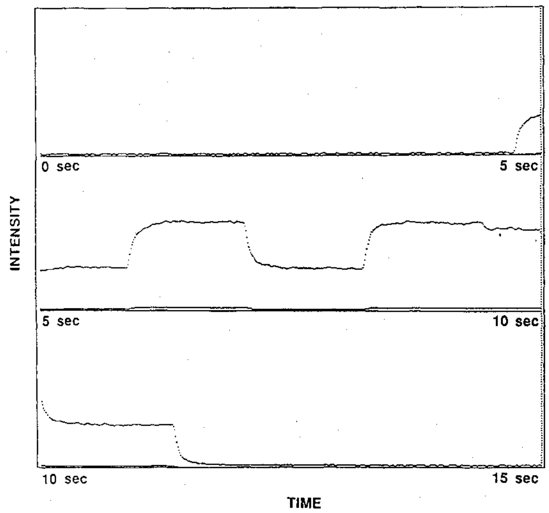

Fig. 13 SKIRT CVF 4.5-μm signal intensities during thruster firings.

the sensor was pointed into the Shuttle's wake. LWIR emissions have been identified as rotationally hot water.[14] These emissions are from water that has been produced by the shuttle and is then collisionally excited by ambient atomic oxygen.

Given what is known from IR/VIS/UV measurements, the following reactions contribute to the Shuttle glow. Incoming O atoms react with the spacecraft plow cloud and on the vehicle surfaces to form NO^* and NO^+. The radiative decay of these species is seen in the infrared. NO is also adsorbed on the spacecraft surface, where it can be desorbed by incoming O atoms and then radiatively decay. Or it can combine with O atoms to form excited NO_2^*. The NO_2^* also desorbs from the surface and radiatively decays, causing the visible glow.

STS-39 obtained Shuttle-glow data only at one altitude. To measure glow at various altitudes, SKIRT was reflown on STS-62 in March 1994 as part of the Experimental Investigation of Spacecraft Glow (EISG). This was a 14-day mission and included elliptical orbits ranging from an apogee of 300 km to a perigee of 194 km. In addition, N_2 releases were observed. Results from this mission will be presented in a later paper.

Conclusion

The SKIRT cryogenic infrared spectrometer onboard STS-39 Discovery obtained the first infrared spectra of Space Shuttle glow. Analysis shows NO, NO^+, and OH are components of Space Shuttle glow. During times when Shuttle contamination-producing events were inhibited and the sensor was pointed in the ram direction, the intensities of the quiescent Space Shuttle glow in the 1–5.4-μm spectral region were on the order of 10^{-9} W/cm^2 sr μm. During thruster firings there were 10- to 100-fold increases in the thruster-enhanced Space Shuttle glow radiance intensities, as well as changes in observed spectral distributions. The glow also depends on the ram angle. As the sensor's field of view changed from looking directly into ram to away from ram, there was a decrease in glow intensities. This corresponds to a decrease in the atomic-oxygen flux onto the surrounding surfaces traveling at 8 km/s. This is consistent with visible-light observations. The decrease of infrared glow intensity as a function of angle from the velocity vector follows a $\cos^2\theta$ curve. During an NO gas release the SKIRT visible radiometers showed a dramatic increase in Shuttle glow intensity. At the end of the NO release there was a two-slope decay of the signal back to quiescent glow signal levels. The first slope was a rapid decay, which then changed to a slower rate. This is consistent with Space Shuttle glow being both a short-lived gas-phase reaction and a slower surface-mediated reaction. During quiescent Shuttle conditions with the sensor field of view pointing away from ram toward deep space, there was no observable glow down to the SKIRT noise level of approximately 10^{-10} W/cm^2 sr μm. This demonstrates that very sensitive cryogenic infrared sensors can operate from the Space Shuttle cargo bay under appropriate conditions. The results of the SKIRT Space Shuttle glow measurements will be used in the design and operation of LEO vehicles to mitigate and exploit the effects of the Earth's upper atmosphere on electro-optical observation systems and spacecraft structures and components.

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