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Infra-red rocket glow: A mechanistic analysis

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Abstract. A two channel infra-red radiometer observed a contaminating glow at 1.53 μm on the up and down legs of a rocket flight between 90 and 105 km. No contamination was detectable at 1.27 μm nor by broadband uv/visible photodiode photometers. The structures in the glow showed a remarkable similarity with the structures on the simultaneously measured atomic oxygen profile. We have been able to show that the glow can be successfully modelled by $I \propto [O]^2 v^2$, where v is the rocket speed. This implies that two oxygen atoms arriving on the surface are involved in the production of the emitting species. It is suggested that the oxygen atoms form a molecule which is either radiatively stabilized or undergoes an association/dissociation with a surface adsorbed oxygen molecule.

Introduction

The occurrence of spacecraft and rocket glows is a well documented phenomenon (see for example GRL special issue 1983). However, their origins are not completely understood. There appear to be a number of distinct types of glows that are both altitude and vehicle type dependent. These glows are summarized in Table 1 and encompass a range of phenomena from the apparently line, or band, emissions such as the features detected in the Dynamics Explorer Fabry-Perot measurements [*Yee et al.*, 1984; *Copeland and Slanger*, 1990] and identified as OH, to continua of the type seen on the Space Shuttle [*Swenson et al.*, 1985]. Reports of rocket glow are almost as old as rocketry itself with accounts of downleg or wake contamination being the most prevalent [*e.g. Heppner and Meredith*, 1958; *Wallis and Anger*, 1968; *Greer et al.*, 1983]. In many of these cases, although the authors may have rejected the hypothesis, we believe that those glows were probably due to an interaction between the vehicle exhaust gases and the atomic oxygen present in the height region over which the glow is seen. However, *López-Moreno et al.* [1985] have reported an infra-red glow observed in front of the rocket at a number of wavelengths between 1.55 μm and 1.70 μm that is the most similar to the glow reported here. Although they could not observe any vehicle-induced emission at 1.27 μm, they could not exclude the possibility of a contribution at that wavelength. López-Moreno et al. concluded that the observed glow was due to hydroxyl radicals excited through the interaction of atomic oxygen with surface adsorbed hydrocarbons as suggested by *Slanger* [1983]. *Murtagh et al.* [1987] have also reported a contamination in front of a rocket during a previous attempt to measure the Meinel emissions in twilight. That glow was seen at approximately 720 nm, both for filter positions that included and excluded the OH (8,3) band, and had an intensity of about 0.5 R/Å. The authors suggested that the contamination may have been auroral in origin but the lack of other data made a definite identification impossible. In the present paper we report the observation of a rocket glow at 1.53 μm and utilize simultaneous measurements of atomic oxygen to characterize the molecularity of the glow.

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Instrumentation

The NLC-93 DECIMALS-B rocket

The data presented here were obtained with instrumentation contained on the DECIMALS-B rocket flown from Esrange. This was accompanied by falling sphere Viper Darts for density, and hence temperature, measurements. The instrumentation included in the payload is listed in Table 2, although this paper will discuss only data from the WIRR and the ORFA experiments. The WIRR is a two channel IR radiometer with Peltier cooled InGaAs detectors. The passbands at 1270 nm and 1530 nm were designed to isolate the $O_2(a^1\Delta_g - X^3\Sigma_g^-)$ and OH (3,1) airglow emissions, respectively. The fields of view (FOV) of the radiometer channels, 6° full angle, were aligned at 30° to the rocket axis with an azimuth separation of 60°. The ORFA experiment consists of two 130.4 nm oxygen atom resonance lamps that illuminate the atmosphere. Both the attenuation of the lamp signals, over two different path lengths, and the resonantly scattered radiation are used in the determination of the distribution of atomic oxygen with altitude [*J. Gumbel, private communication*].

The flight took place at 0102 UT, on 2 August 1993, from Esrange, Sweden (67°50′ N 21°06′ E). At this time the mesosphere was sunlit, solar zenith distance 90°41′, and the mesopause region was extremely cold with the minimum temperature around 130 K [*F. Schmidlin, private communication*]. The rocket reached an apogee of 104.6 km. Stable precession was attained at about 66 km, soon after motor separation; the precession half angle was 3.0°, as determined from the gyro data, and the precession period 4.4 s.

Data Analysis

As the rocket spun, the fields of view of the WIRR instrument were swept around the sky and covered a large range of solar scattering angles. However, during a part of each roll there was direct solar illumination of the openings in the rocket skin through which the WIRR observed, and the measured signals were subject to severe contamination. Only those data obtained when the fields of view were in the

Table 1. Types of Spacecraft Glow That Have Been Reported

Glow type	Altitude range	Behaviour	Possible Mechanism
"Shuttle Glow"	180-350 km	Continuum 400 - 800 nm peaking ~680 nm, Band emission 1.7-3.0 μm & 4.5-9.5 μm	NO + O on surface[a] H_2O + O in outgassing cloud[b]
"UV glow"	160-230 km	LBH emissions	$O/N_2 + N_2 + N_2$ in gas phase[c]
AE /DE - Glow	140-280 km	280 -732 nm $z > 180$ km; $I \propto [O]$ $z < 180$ km ; $I \propto [N_2]^2$	$O + H_2O \rightarrow OH + OH$ $O + R\text{-}H \rightarrow R\bullet + OH$[d]
Downleg rocket glows	90-110 km	275 - 762 nm Spin and precession modulated	Interaction of exhaust gases with atomic oxygen[e]
Upleg rocket glows $v>2$ km s^{-1}	40 -95 km	High apogee rockets	Dissociation and recombination in shock front[f]
Upleg rocket glows $v<2$ km s^{-1}	85-105 km	IR glow related to [O]	See text[g]

[a][*Swenson et al.*, 1985; *Caledonia et al.*, 1993].
[b][*Meyerott et al.*,1994]
[c][*Conway et al.*, 1987; *Huffman et al.*, 1980].
[d][*Abreu et al.*, 1985; *Slanger*, 1983; *Yee and Abreu*, 1983; *Yee et al*,. 1984, 1985].
[e][*Wallis and Anger*, 1968; *Greer et al.*, 1983].
[f][*Clemesha et al.*, 1987, 1988, *Erdman et al.*, 1993; *Erdman et al.*, 1994; *Levin et al.*, 1993; *Levin et al.*, 1994].
[g][*López-Moreno et al.*, 1985]

rocket shadow were used in the analysis. Extraction of the airglow signals was facilitated by decomposing the data into roll scans and then using the gyro roll signal to average the data into 2° roll bins. At a spin rate of 5 Hz this procedure resulted in 960 spin scans between 60 km altitude on the up- and down-legs of the flight. To allow the maximum time for recovery from the solar contamination, only data from the last two roll bins before leaving the shadowed region have been chosen for detailed analysis. However, a similar analysis for the earlier roll bins supports our present findings.

The variation of the total measured radiance as a function of the rocket altitude is shown in Figure 1a and the major features of the profile are also indicated. A Rayleigh scattered component is clearly seen, as is the passage through the noctilucent cloud layer at 82.5 km. Confirmation of the identification of the NLC layer is provided by a comparison with the signal from the wide band MiniSLIPS photometer, shown in Figure 1b. Above 85 km the expected decrease in intensity on penetration of the OH airglow layer is observed but is abruptly ended by a large contaminating glow with a peak irradiance of about 30 kR. This corresponds to about 30 R/Å across the 100 nm FWHM filter passband.

The Rayleigh scattered component was isolated by using a least squares technique to fit the region between 66 and

Table 2. The DECIMALS-B Instrumentation

Instrument name	**Purpose**
PIP (Positive ion probe)	Turbulence measurements
MiniSLIPS (Miniature Scattered Light Intensity Profile Sensor)	Scattered light measurements for NLC detection
SLIPS (Scattered Light Intensity Profile Sensor)	Scattered light measurements for NLC detection
Field Mill	Electric field measurements
WIRR (Warm Infra Red Radiometer)	1.27 μm $O_2(a^1\Delta_g)$ and 1.53 μm OH dayglow.
Capacitance probe and Faraday Experiment	Plasma environment measurements
PAT (Particle and Aerosol Trap)	Ion and particle impact measurements
ORFA (Oxygen Resonance Fluorescence and Absorption)	In-situ measurement of the atomic oxygen profile

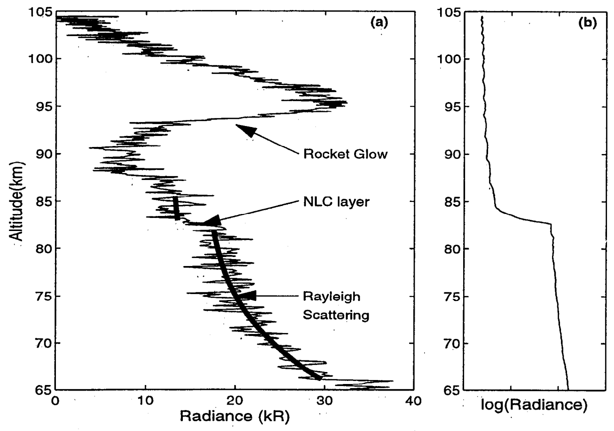

Figure 1. (a) The measured vertical radiance on the 1530 nm channel, (b) The radiance registered by the MiniSLIPS photometer.

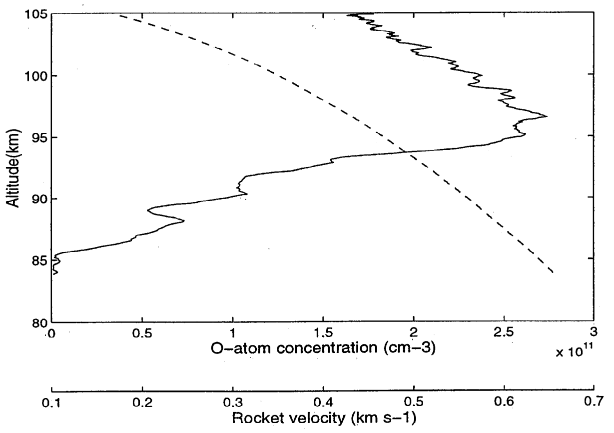

Figure 3. The atomic oxygen distribution measured by the resonance fluorescence and absorption technique on board the DECIMALS-B rocket. The dashed line shows the rocket velocity.

82 km to the integral of the number density above the height in question [*Murtagh et al.*, 1987]. The Rayleigh component, plus background, was expressed as:

$$I_{Ray} = A + B\int_{z}^{\infty} n\, dz \qquad (1)$$

where the constant, A, includes the contributions at the upper limit of the fit due to scattering from the cloud layer particles, the OH emission and any background that has not already been removed, the constant, B, contains all factors such as the Rayleigh scattering cross-section, the solar irradiance, *etc.* The required number density in Equation 1 was obtained from a model atmosphere that was constructed with information from the passive falling sphere [*F. Schmidlin, private communication*] flown within 20 minutes of, and along the same trajectory as, the DECIMALS-B flight. This was combined with an appropriate MSISE-90 [*Hedin*, 1991] temperature profile for the heights above 90 km. Once Equation 1 has been fitted, the second term of the expression can be used to remove the Rayleigh scattering contribution.

Figure 2 shows the result of using this fit to remove the cloud and Rayleigh components. The constant radiance below 85 km indicates that the emission originates above this altitude, as is the case for the OH Meinel emission. Above the hydroxyl emission, the radiance increases rapidly, indicating the presence of a locally-produced glow emission.

This glow appears to begin at about 87 km altitude, maximize at 96 km, and then decrease in radiance towards apogee. Comparison of the glow signal with the atomic oxygen profile measured simultaneously (Figure 3), shows remarkable similarities between both the general shape and the small scale structures seen on the upper side of the peak. Through a series of comparisons we have found that both the shape of the glow and the structures present on it are best represented by $[O]^2v^2$, where v is the speed of the rocket. Thus, the emission intensity is proportional to the square of the atomic oxygen flux. This glow model is represented by the heavy line in Figure 2 and has been normalized so as to match the measured glow signal at 97 km altitude. Any attempt to include the ambient density in the glow model, or to modify the dependence on the speed of the rocket, results in an unsuitable altitude distribution for the glow. From an investigation of the glow signal at other spin phases it has been possible to confirm that the glow was present over the range of observation angles that were not affected by solar contamination. This corresponds to angles between 85° and 140° from the trajectory plane, where 0° is the forward direction; the corresponding solar scattering angles are between 66° and 96°. The intensity of the glow appears to be constant, within the uncertainties, for this range of angles with respect to the trajectory plane, although there is, perhaps, a slight tendency to weaken towards the wake direction.

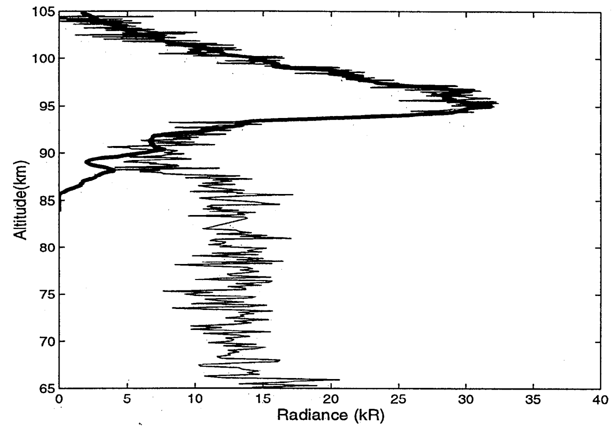

Figure 2. The radiance profile after removal of the Rayleigh and cloud components. The modelled glow signal is shown as the heavy line.

Discussion and Conclusions

For the first time it has been possible to closely compare an observed rocket glow with the simultaneously measured atomic oxygen distribution. The behaviour of the glow is similar to that observed by *López-Moreno et al.* [1985] and has a very similar intensity. Following the suggestion of *Slanger* [1983] those authors chose to attribute the glow to hydroxyl radicals that were produced through a reaction between the impinging atomic oxygen and hydrocarbons adsorbed on the surface of the vehicle. However, the present observations indicate that there are two oxygen atoms involved in the process creating the glow, and it is difficult to see how OH could be formed in two stages. A first stage in a process involving two O-atoms could be their association to form a metastable oxygen molecule (O_2^*) in any of the states known in the nightglow or laboratory. In the best case, most of the association energy would still be available in the metastable molecule for further reactions. Should a reaction with a water molecule then occur there may be sufficient energy to produce an OH radical. However, it is unlikely that there would be energy available in this mechanism to excite the product radical to the vibrational states required, $v' = 3$ for these observations, to act as the source of the glow.

Another possibility is that the O_2^* either combines with an O_2 molecule on the surface of the vehicle to form O_4 which subsequently dissociates with the emission of radiation, or that there is a radiative relaxation of the O_2^* to a stable state. The first of these processes is a variant of one that was considered by *Bates* [1993] as a possible source of the nightglow continuum. Bates suggested that if the combining molecules were both in the $O_2(a^1\Delta_g)$ state then the emission would be in the near infra-red, but he dismissed the possibility of an association between O_2 molecules in the ground ($X^3\Sigma_g^-$) and ($a^1\Delta_g$) states as there was not enough energy to generate the nightglow continuum at the visible wavelengths observed. However, the present investigation cannot preclude this reaction as a possible source of an infrared continuum as the presence of a 30 kR signal at 1.27 µm, equal to the contamination intensity recorded here, would not be readily detected in the presence of the strong (>100 kR) infrared atmospheric band emission at the contaminant altitude [*Murtagh et al.*, 1995]. The second process, in which the combining oxygen atoms form a molecule in the repulsive $1^3\Pi_u$ state, has been considered by *Dalgarno et al.* [1992] who note that the emission from such a process would be beyond 5 µm, although the calculated recombination rate could match the requirements of the present observations. The observed glow would require that only 1 molecule in 10^6 radiate in the FOV.

In conclusion, the infrared glow measured on the upleg of the DECIMALS-B flight has been shown to be correlated with the local atomic oxygen density. Although the excitation mechanism cannot be clearly identified, the intensity variation, which is proportional to the square of the atomic oxygen flux to the vehicle, suggests that the first step in the excitation process involves the formation of an excited oxygen molecule. This molecule is then either radiatively stabilized, or undergoes an association/dissociation with a surface adsorbed oxygen molecule. The observations also suggest that it may be possible to infer the local structure in the [O] profile from the height variation of the ram glow.

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