Discovery of the FeO orange bands in the terrestrial night airglow spectrum obtained with OSIRIS on the Odin spacecraft


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1. Introduction

[2] The terrestrial night airglow spectrum has been studied quantitatively for more than a century. Early ground-based studies indicate the first measurement of the wavelength of the mysterious “green line” by Ångström [1869], reported as 5567 Ångström. McLennan and Shrum [1925] identified the source of the green emission as a transition from the OI metastable \(^{1}S_0\) state to the \(^{1}D_2\) state. Barbier et al. [1951] analyzed dual wavelength observations of the green emission to establish an accurate background correction and confirmed the presence of an underlying terrestrial based continuum, in addition to the star background and zodiacal light inherent in ground-based observations. Sternberg and Ingham [1972] reviewed the previous night airglow continuum observations and, after removing the non-terrestrial sources, calculated the absolute continuum differential brightness at a series of wavelengths in the visible and near infrared from their spectrometric observations, conducted at Observatoire de Haute Provence at approximately 44° North. They found the continuum peaks around 600 nm and noted its similarity to the \(NO + O \rightarrow NO_2^*\) chemiluminescent air afterglow spectrum.

[3] A number of observations of the \(NO_2^*\) air afterglow emission have been made at higher latitudes. In a series of rocket flights into auroral displays Sharp [1978] observed the \(NO_2^*\) air afterglow emission peaking between 100 and 110 km. Witt et al. [1979, 1981] observed the \(NO_2^*\) air afterglow in the auroral zone but with no aurora in the field of view. During the ETON rocket campaign, conducted at approximately 57° North, McIver et al. [1986] observed the maximum brightness in the vertical profile of the 540 nm night airglow continuum at approximately 98 km along with a fainter second layer at approximately 90 km. Using spectrometric limb observations from the space shuttle STS-30 mission Mendes et al. [1993] observed a green continuum at 103 km ± 2 km at low latitudes.

[4] Bates [1993] provided a critical analysis of the proposed night airglow continuum source mechanisms and suggested that the \(NO_2^*\) air afterglow contributes only a fairly small fraction of the total. From a series of observations that covered the complete southern hemisphere Gattinger et al. [2010] concluded that the \(NO_2^*\) night airglow emission is much brighter at polar latitudes than at low latitudes. Accordingly, attempts to detect faint emissions in the night airglow spectrum are more likely to succeed at lower latitudes. The chemiluminescent \(NO + O \rightarrow NO_2^* + O_2\) reaction also produces emission in the 600 nm region [Clough and Thrush, 1967] and can potentially contribute to the airglow signal, although Bates [1993] concluded that for this mechanism “the contribution to the nightglow is inappreciable”.

[5] Recently, Cosby and Slanger [2007] assembled a night sky spectrum from the echelle spectrograph and imager (ESI) on the Keck II telescope on Mauna Kea, approximately 20° north latitude. The spectrum shows a structured continuum in the 550 to 650 nm region that does not match the spectral shape of the chemiluminescent \(NO + O \rightarrow NO_2^*\) emission. Jenniskens et al. [2000] observed a similar structurally structured continuum in the 550 to 650 nm region in a Leonid meteor persistent train and noted the spectral match with the laboratory spectrum of the FeO “orange bands”. The primary focus of the current analysis is this 550 to 650 nm structured continuum observed in the terrestrial night airglow spectrum at low latitudes. The observations, made with the OSIRIS space-borne limb-scanning spectrograph, and the spectral isolation procedures, are discussed in the...
The 350 nm to 750 nm observed night airglow limb radiance spectrum averaged from 80 to 92 km tangent limb altitudes. Data are from five 24 hr observing periods between 20 April 2003 and 27 May 2003, between the Equator and 40° South. Observations in the 480 nm to 530 nm OSIRIS order sorter region are omitted. (b) Solid: Matching synthetic spectra of the O₂ Herzberg, Chamberlain and Atmospheric band systems, the OH vibration-rotation system and the Na doublet. DotDash: Estimated upper limit (scaled up by ten times) of the NO + O → NO₂* component. (c) The difference signal, Figure 1a spectrum minus Figure 1b spectrum, with expanded vertical scale. The data gap over the 480 to 530 nm region in the observed OSIRIS spectrum is due to the order sorter.

following sections. The volume emission rate (VER) altitude profile of the structured continuum is compared with other emission features present in the observed spectrum. A brief discussion of possible source mechanisms for the 550 to 650 nm continuum is also presented.

2. Instrumentation and Observations

The observations reported here are from the Optical Spectrograph and Infra-Red Imager System (OSIRIS) [Llewellyn et al., 2004] on the Odin spacecraft [Murtagh et al., 2002]. The Odin spacecraft was launched on 20 February 2001 into a circular Sun-synchronous orbit, ascending node 1800 Local Time, orbit inclination 97.8°, and altitude 620 km. In aeronomy mode the OSIRIS field of view is scanned vertically across the tangent limb with a vertical field of view of 1 km, a scanning rate of approximately 0.75 km s⁻¹ and exposure times typically 2 s in the upper mesosphere and lower thermosphere. Absolute pointing knowledge at the limb tangent point is known to be better than one-half kilometer. As OSIRIS has a spectral imaging CCD detector, all emissions in the 275 to 815 nm wavelength range are exposed simultaneously facilitating the accurate determination of relative spectral intensities. The spectral resolution is approximately 0.90 nm.

To obtain reliable emission ratios that are separated widely in wavelength, an accurate relative spectral calibration of the OSIRIS instrument is essential. Pre-launch calibrations used NIST calibrated standard lamps followed by on-orbit astronomical observations to refine the calibration. The resulting absolute calibration error is estimated to be ±10% and the precision approximately 5%. During the mission, response changes are monitored by a comparison between the observed on-orbit daytime limb scatter spectra and simulations using the SASKTRAN three-dimensional radiative transfer model described by Bourassa et al. [2008]. Multiple Rayleigh molecular scatter, Mie aerosol scatter, molecular atmospheric extinction and Lambertian ground albedo effects are included in the model. Using auroral emissions observed by OSIRIS at multiple wavelengths and with common upper states, Gattinger et al. [2009] confirmed the accurate relative calibration in the ultraviolet and blue regions.

Spectra from individual limb scans are analyzed over the 75 to 105 km limb tangent altitude range. For each limb scan a slowly changing CCD dark pattern is determined from the exposures in the 105 to 110 km tangent altitude range and subtracted from the observed tangent limb spectra. This background subtraction procedure automatically removes any non-terrestrial emission sources. Only those spectra for which the solar zenith angle was greater than 101° were considered in the analysis to exclude the effects of scattered solar radiation.

An averaged airglow spectrum from 350 to 750 nm, limb altitude range from 80 to 92 km, is shown in Figure 1a. The spectrum is from latitudes between the Equator and 40° south over five 24 hr observing periods between 20 April 2003 and 27 May 2003. Latitudes poleward of 40° have been excluded in order to minimize the contribution of the chemiluminescent NO + O → NO₂* reaction arising from enhanced NO in the dark polar regions [Gattinger et al., 2010].

The obvious airglow features are the OI (1⁰S → 1⁰D) atomic line at 557.7 nm, the Na emission doublet centred on 589.3 nm and a number of OH vibration-rotation bands. The weak emissions in the ultraviolet region are from the Herzberg and Chamberlain band systems. Faint emission features arising from the O₂(b¹Σ⁺−X¹Σ⁻) band system are present in the 710 nm spectral region. In addition to these known emissions there appears to be an unidentified ‘continuum’ feature in the 600 nm region. Procedures for spectrally isolating this underlying continuum are described in the next section.

3. Spectral Analysis

Model spectra of band systems known to be present in the night airglow were generated for comparison with the observed spectral features in Figure 1a. Each of the model spectra were convolved with the approximately 0.90 nm OSIRIS instrumental function before scaling to the observed spectrum. For the ultraviolet and blue spectral regions the O₂ Herzberg and Chamberlain band model is from the tabulations by Cosby et al. [2006]. The model spectrum was scaled by comparison with the observed OSIRIS spectrum over the 350 to 400 nm region. For the visible and near infrared regions synthetic spectra of the OH Meinel bands were generated using the ground-based relative band
The difference spectrum from Figure 1c, arbitrarily smoothed to improve presentation, compared with a scaled laboratory spectrum of the FeO orange bands.

The calibrated airglow spectrum shown in Figure 1c and the composite model spectrum in Figure 1b is shown in Figure 1c. It should be noted that the NO + O contribution is at most a minor source. From preliminary spectral simulations of the FeO bands a change in vibrational distribution, potentially caused by collisional quenching at the much higher laboratory pressures, can indeed cause the observed spectral differences.

As a further investigation of the source of the 590 nm emission feature in Figure 2 the data have been compared with independent atmospheric measurements. For example, using LIDAR observations of Fe and Na at 40° north lat...
measurements of the STRATOGLOW NO$_2^*$ mechanism [Evans and Shepherd, 1996]. Thus we are confident in our conclusion that the emission is due to FeO.

[18] Following our discovery of the FeO 'orange bands' emission in the nightglow Slanger and co-workers (D. V. Saran et al., FeO emission in the mesosphere: Detectability and diurnal behavior, submitted to Geophysical Research Letters, 2010) have used data collected with both the ESI spectrograph on the Keck II telescope and the UVES spectrograph on the Very Large Telescope (VLT) in Chile to study the temporal variation of the FeO emission. Their results show that the FeO emission can exhibit dramatic temporal changes.

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References

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