SPECTRUM OF THE EXTREME ULTRAVIOLET NIGHTGLOW AS MEASURED BY EURD *

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Abstract. After 2 years of operation onboard the Spanish satellite MINISAT, EURD has achieved an unprecedented success in the observation of the terrestrial nightglow in the EUV, covering a range of $\sim 350 - 1100$ Å. EURD has provided a total of more than 543 hours of integration in the long wavelength spectrometer and more than 898 hours in the short wavelength one, allowing the achievement of the most detailed atlas of the terrestrial EUV nightglow ever obtained. We present here the spectra obtained, together with the identification of the lines, some of them detected for the first time in the nightglow. These spectra represent an improvement in sensitivity of several orders of magnitude with respect to previous observations. It has been possible, for the first time, to identify the complete Lyman series of atomic hydrogen, resolving up to Lyman-ϵ. It has also been possible to identify the helium Lyman-β line at 537 Å and to detect other lines of the blended Lyman series of helium, at 515 and 522 Å. The spectra clearly show the presence of the O II lines at 617, 644, 673, and 718 Å, previously observed in the dayglow but seen here for the first time in the nightglow. In addition to the recombination continuum of the atomic oxygen at 911 Å, two features of O I have been detected in the nightglow: the 3s$'$ ^{3}D$_o$ transition at 989 Å, previously observed by Chakrabarti (1984) and the 2p^{3}4s^{3}S^o transition at 1040 Å, partially overlapped with Lyman β, but clearly distinguishable from it. This feature has been seen for the first time in the terrestrial nightglow. The radiative recombination continuum of atomic oxygen at 911 Å, that was absent in the observations of the first year of operation of EURD, is now clearly visible. The reasons of the absence of the O I feature during the first year of operation are still unknown. Anderson *et al.* (1976) also noticed a strong variation with time of this 911 Å emission.

1. Introduction

EURD (Espectrógrafo Ultravioleta extremo para la Radiación Difusa) is an instrument developed to study the extreme ultraviolet (EUV) diffuse radiation. EURD is

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onboard the Spanish satellite MINISAT-01, launched on April 21, 1997. Its orbit is retrograde with an inclination of 151° and an altitude of 575 km. EURD observes in the anti-sun direction to minimize possible contamination of scattered solar radiation at these wavelengths. The observations are centered at orbital midnight time, with the line of sight towards the Earth's shadow cone, and cover a zenith angle range from $-90°$ (atmosphere just before ground dawn) to $+90°$ (just after dusk).

2. Description of the Instrument

EURD consists of two spectrographs that cover a bandpass from 350 to 1100 Å with 5 Å spectral resolution. Both spectrographs perform simultaneous observations with a field of view of $25° \times 8°$. The design of the spectrographs are described in detail in previous publications (see Morales *et al.*, 1996; Bowyer *et al.*, 1997). They basically consist in a new compact, fast optical system optimized for diffuse spectroscopy, a novel, low noise microchannel plate photon detector, and a mechanical filter wheel that permits an accurate determination and correction of the expected background (internally scattered hydrogen Lyman α radiation and detector background). The detector is surrounded by an anticoincidence shield that allows the identification and rejection of at least 80% of the energetic particles penetrating the detector.

Since EURD is pointing in the antisolar direction and the observations are made during orbital eclipse, as the satellite moves in the shadowed part of the Earth atmosphere, the measured radiation comes from regions above MINISAT orbit (575 km). Therefore, the possible contributors are interplanetary and interstellar medium, geocoronal radiation and a small fraction of emission coming from the low earth exosphere.

3. Results and Discussion

In a previous paper (López-Moreno *et al.*, 1998) a spectrum of the terrestrial nightglow in the EUV range was presented based in the measurements made by EURD during its first year of operation. The data corresponded to an integration time of $\sim$ 600 000 s (166 hours) and, at that time, it provided the spectrum with the best sensitivity ever obtained in the EUV. Now, after accumulating a total of more that 3 318 000 s (898 hours) of measurements, the signal to noise ratio has increased to allow a background noise level of less than 100 photon cm^{-2} s^{-1} sr^{-1} Å^{-1}, equivalent to 1.26 10^{-3} R Å^{-1}.

The values obtained for the intensity in López-Moreno *et al.* (1998) were based in the ground calibration and were accurate to 50%. A better calibration using standard stars and moon emission (see Bowyer *et al.*, 1999) allows an accuracy of the EURD results better than 20% for the whole spectral range.

There are very few spectroscopic measurements of this spectral region. Kumar *et al.* (1974) obtained the first spectrum in the range from 770 to 1050 Å with a resolution of 40 Å with instrumentation onboard a rocket, and they were able to detect and identify the OII line at 834 Å and a feature between 950 and 1050 Å that tentatively attributed to either the Birge Hop Field band of N_2, OI at 1027 Å, or HI at 1025 Å. Anderson *et al.* (1976) presented the observations of the NRL extreme ultraviolet experiment onboard the STP 72-1 satellite in the 800–1050 Å region. They interpreted the main feature in their bandpass as arising from the recombination continuum of atomic oxygen at 911 Å. They also found a strong seasonal and latitudinal dependence of the emission along two years of observations.

Chakrabarti *et al.* (1984) published a spectrum of the nightglow with a resolution of 8 Å, taken by the STP 78-1 satellite. In that work a range from 300 to 1400 Å was covered and they presented separated spectra for down-looking and up-looking observations. They identified the Lyman β line at 1026 Å as well as the geocoronal HeI line at 584 Å. They also detected for the first time in the nightglow the 834 Å line of OII, previously observed in the dayglow (Chakrabarti *et al.*, 1983).

Feldman *et al.* (1992), using the Hopkins Ultraviolet Telescope (HUT) during the Astro-1 Space Shuttle Mission (STS-35), which observed at zenith angles from 77° to 95° from an altitude of 358 km, have presented the most detailed spectrum of the nightglow up to date. With a spectral resolution of 3 Å, it covers the range between 830 and 1830 Å. In the range where EURD spectra overlap those of HUT (830 to 1100 Å), they detected Lyman β, the recombination continuum of atomic oxygen at 911 Å and a weak feature at 989 Å that they tentatively identified as corresponding to OI. Holberg (1986) analyzed the interplanetary medium data obtained by the ultraviolet spectrometer on board Voyager 2. The spectrum, in the range from 500 to 1200 Å, is dominated by the HI Lyman series, including: Lyman-α at 1216 Å (with a brightness of 1081 R), Lyman-β at 1026 Å (2.39 R) and the first identification of Lyman γ at 973 Å (0.565 R) in the interplanetary medium, together with HeI at 584 Å with a brightness of 1.2 R.

Recently, Jelinsky *et al.* (1995) analyzed the observations of the Extreme Ultraviolet Explorer (EUVE) in the wavelength range 160–740 Å. They were able to detect the HeI Lyman α line at 584 and the rest of the HeI Lyman series, and estimated intensities similar to our observations: 1.3 R for Lyman α and 4.0×10^{-2} R for the rest of the helium Lyman series, mainly corresponding to Lyman β at 537 Å. EURD has enough spectral resolution to discriminate He Lyman β from the rest of the series that appear blended at the EURD spectral resolution. The values obtained by EURD are 2.3 and 4.1×10^{-2} R respectively.

Figure 1 shows the spectra covering from 400 to 1050 Å, combining the results obtained by the two spectrographs. The one at the top corresponds to the measurements taken at low ($< 70°$) zenith angles while the one at the bottom contains data obtained at zenith angles $> 70°$. Both spectra are calculated by averaging the profiles obtained at different zenith angles, after correcting for the emission variations due to the different paths of the line of sight depending on the zenith

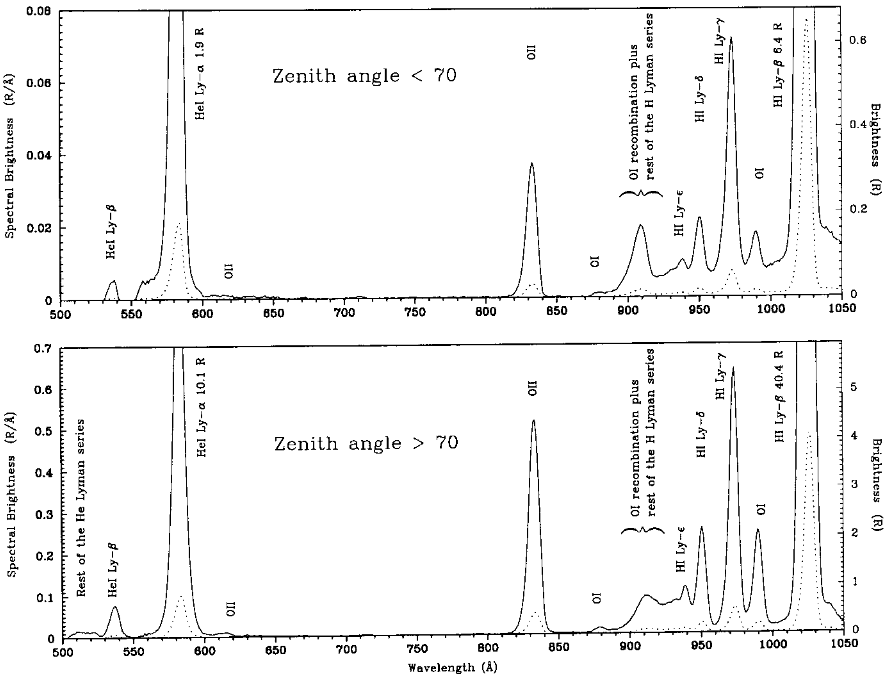

Figure 1. Extreme ultraviolet spectra, from 500 to 1050 Å, obtained by EURD after more than 898 hours of observation, for zenith angles $< 70°$ (top) and between 70° and 90° (bottom). Note the different scales for these two spectra. The dotted lines represent the spectra divided by 10, to fit all lines within the frame.

angle (an approximate cosine law). Hence the possible difference between them cannot be due to this geometrical effect but to different physical conditions of the observed region.

The spectra show a number of lines that EURD has detected for the first time. The lines we have unambiguously identified are listed in Table I with the lines observed in earlier observations by other authors. It can be seen that we have detected and resolved the Lyman series lines of geocoronal atomic hydrogen, from Lyman α to Lyman ϵ. We identify the emission between 912 and 938 Å as the rest of the Lyman series, all blended together. Our instrument has enough sensitivity to detect this emission, but not enough spectral resolution to separate it into individual lines. Two bright features are superimposed on the Lyman series: the $3s^3D^o$ transition of OI at 989 Å and the recombination continuum of OI at 911 Å. It is worth to noting that the feature at 911 Å was absent during the first year of observations.

We have calculated a fit of the Lyman series of hydrogen considering that the population of each level obeys a Boltzman distribution:

$$N_k/N_i = g_k/g_i \times e^{-(w_k-w_i)/kT} \quad (1)$$

and that the emission is proportional to the Einstein coefficient of spontaneous emission

$$I_{ki} \propto A_{ki} N_k \quad (2)$$

and we have smoothed the numerical spectra to the resolution of EURD.

We have applied the fit to both spectra shown in Figure 1, and obtained that the temperatures that best fit the measurements are very different for the two of them. The spectrum for smaller zenith angles, which is more representative of interplanetary hydrogen (since the contamination of the geocorona is minimized), is reproduced by a temperature of 5500 K. The spectrum for the larger zenith angles, that includes resonant scattering from lower regions of the geocorona, is best fit with a temperature of 7500 K, suggesting that processes occurring in the Earth exosphere, which include ionization of H followed by recombination, may be responsible for the higher electronic temperature.

The identification of the Lyman series of helium is straightforward from our spectra. The clear identification of the first two lines of the series, at 584 Å and 537 Å also allows us the measurement of the apparent temperature of helium. In this case, as it was clearly seen with hydrogen, the values of the temperatures that best fit the observation are different, depending on the geometry of the observation. We obtain a value of 7600 K for the spectrum at lower zenith angles and a value of 12200 K for the spectrum taken at zenith angles greater than 70°.

Table I presents the list of features identified in the spectra. There is a number of them that have been detected for the first time, together with some others previously seen in the nightglow but with a much lower S/N ratio. Apart from the already mentioned Lyman series of hydrogen and helium, EURD has detected the second spectral order of the bright feature of HeII at 304 that dominates the EUV in that region.

The list also shows the four most intense transitions of the OII at the following wavelengths: 617 Å (3s ^{2}P – 2p^3 ^{2}D^0), 644 Å (2p^4 ^{2}S – 2p^3 ^{2}P^0), 673 Å (3s ^{2}P – 2p^3 ^{2}P^0), and 718 Å (2p^4 ^{2}D – 2p^3 ^{2}D^0).

These lines were observed by Feldman *et al.* (1981) in the dayglow using an spectrometer of 6.5 Å onboard a rocket that reached an apogee of 265 km. Chakrabarti *et al.* (1983) also identified the lines from a satellite at 600 km of altitude with the instrument pointing to the nadir but they were not detected, even in the dayglow, when the instrument was pointing near the zenith. Its identification by EURD is a proof of its extremely low limit of detection.

TABLE I
Nightglow lines detected by EURD

Wavelength (Å)	Short		Long		Identification
	Night	Twilight	Night	Twilight	
508–515	Yes	Yes	–	–	HeI Lyman cont.
539	Yes	Yes	–	–	HeI Lyman β
555	No	Yes	–	–	OII
584	Yes	Yes	Yes	Yes	HeI Lyman α
608	Yes	Yes	Yes	Yes	HeII (304 Å× 2)
617	Yes	Yes	Yes	Yes	OII
631	No	Yes	Yes	Yes	?
635	No	Yes	Yes	Yes	?
645	Yes	Yes	Yes	Yes	OII
650	No	No	No	Yes	?
672	Yes	Yes	Weak	Yes	OII
711	Yes	Yes	No	No	OII
716	Yes	Yes	No	No	OII
747	No	No	Yes	Weak	OI
775	Weak	Weak	Yes	Yes	OII NII
793	No	Weak	No	Yes	OI(792) OII(796)
834	–	–	Yes	Yes	OII
859	–	–	Weak	Yes	NI
878	–	–	Yes	Yes	OI NI
911	–	–	Yes	Yes	OI
938	–	–	Yes	Yes	H Lyman ϵ
950	–	–	Yes	Yes	H Lyman δ
973	–	–	Yes	Yes	H Lyman γ
989	–	–	Yes	Yes	OI
1026	–	–	Yes	Yes	H Lyman β
1040	–	–	Yes	Yes	OI

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References

Anderson, D.E.R., Meuer, R. and Weller, C.S.: 1976, *Planet. Space Sci.* **24**, 945.

Bowyer, S., Edelstein, J. and Lampton, M: 1997, *Astrophys. J.* **485**, 523.

Chakrabarti, S., Kimble, R. and Bowyer, S.: 1984, *J. Geophys. Res.* **89**, 5660.

Chakrabarti, F., Paresce, S., Bowyer, S., Kimble, R. and Kumar, S.: 1983, *J. Geophys. Res.* **88**, 4898.

Feldman, P.D., Anderson Jr., D.E., Meier, R.R. and Gentieu, E.P.: 1981, *J. Geophys. Res.* **86**, 3583.

Feldman, P.D., Davidsen, A.F., Blair, W.P., Bowers, C.W., Durrance, S.T., Kriss, G.A., Ferguson, H.C., Kimble, R.A. and Long, K.S.: 1992, *Geophys. Res. Lett.* **19**, 453.

Holberg, J.B.: 1986, *Astrophys. J.* **311**, 969.

Jelinsky, P., Vallerga, J.V. and Edelstein, J.: 1995, *Astrophys. J.* **442**, 653.

Kumar, S., Bowyer, S. and Paresce, F.: 1974, *Geophys. Res. Lett.* **1**, 109.

López-Moreno, J.J., Morales, C., Gómez, J.F., Trapero, J., Bowyer, S., Edelstein, J.J., Lampton, M. and Korpela, E.: 1998, *Geophys. Res. Lett.* **25**, 2937.

Morales, C., Bowyer, S., Gómez, J.F., Trapero, J., Ulibarrena, M., Gutiérrez, F., López-Moreno, J.J., Pérez Mercader, J., Lampton, M. and Edelstein, J.: 1996, in: *International Conference on Small Satellites: Missions and Technology*, INTA, Madrid, 61.