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EURD Observations of EUV Nightime Airglow Lines†

José J. López-Moreno

Instituto de Astrofísica de Andalucía, CSIC

Carmen Morales, José F. Gómez and Joaquín Trapero[1]

Laboratorio de Astrofísica Espacial y Física Fundamental,INTA

Stuart Bowyer, Jerry Edelstein, Michael Lampton, and Eric J. Korpela

Space Sciences Laboratory, University of California, Berkeley

Abstract. The extreme ultraviolet (EUV) airglow has yet to be studied extensively due to observational difficulties in this range of the spectrum. EURD is an instrument designed to study diffuse EUV radiation flown on the Spanish MINISAT-01 satellite. In this paper we present observations of the terrestrial night airglow as observed from EURD in the range of 400 to 1060 Å. The high sensitivity and high resolution of the instrument, compared with previous observations, and the long integration times provided by MINISAT-01 permits the identification for the first time of the complete Lyman series of atomic hydrogen resolving up to Lyman ϵ. It has also been possible to identify a feature at 537 Å as helium Lyman β line and the detection of other lines of the blended Lyman series of helium at 515 and 522 Å.

Introduction

There are very few spectroscopic measurements of the EUV airglow in the band from 350 to 1100 Å. In 1974 *Kumar et al.* obtained the first EUV airglow spectrum in the range from 770 to 1050 Å with a resolution of 40 Å with instrumentation onboard a rocket. They were able to detect and identify the OII line at 834 Å and a feature between 950 and 1050 Å that was tentatively attributed to either the Birge Hop Field band of N2 , OI (1027) or H at 1025 Å. *Anderson et al.* [1976] presented observations made with the NRL extreme ultraviolet experiment onboard the STP 72-1 satellite covering the 800-1050 Å region. They interpreted the main emission 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 over the two years of observations.

In 1984 *Chakrabarti et al.* published a spectrum of the nightglow at a resolution of 8 Å taken with an instrument flown on the STP 78-1 satellite. In that work a range from 300 to 1400 Å was covered. They presented spectra for both 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 the 834 Å line of OII in the night; it had previously been 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), have presented the highest resolution spectrum of the nightglow. The instrument had a spectral resolution of 3 Å and covered the range between 830 and 1830 Å. Observations were made at zenith angles from 77° to 95° from an altitude of 358 km. 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 OI. *Holberg* [1986] used the ultraviolet spectrometer on board Voyager 2 to obtain a spectrum of the diffuse radiation from the interplanetary medium. A total integration time of 1.5×10^6 s was used. 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 1100 R), Lyman β at 1026 Å (2.4 R) and the first identification of Lyman γ at 973 Å (0.57 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 detected the HeI lines at 584 and 537 Å with intensities similar to our observations (1.3 and 4.0×10^{-2} R respectively).

The data provided by EURD, covering the 350-1100 AA range with a very high sensitivity, represent a significant improvement over previous measurements of the high altitude terrestrial nightglow in the extreme ultraviolet.

Description of the instrument and data reduction

EURD (Espectrógrafo Ultravioleta extremo para la Radiación Difusa) consists of two spectrographs that cover a bandpass from 350 to 1100 Å with 5 Å spectral resolution. The two spectrographs perform simultaneous observations with a field of view of 25° × 8°. The design of the spectrographs are described in detail in previous publications [*Morales et al.*, 1996],[*Bowyer et al.*, 1997]. They basically consist of 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

[1]Also at Instituto de Astrofísica de Andalucía, CSIC

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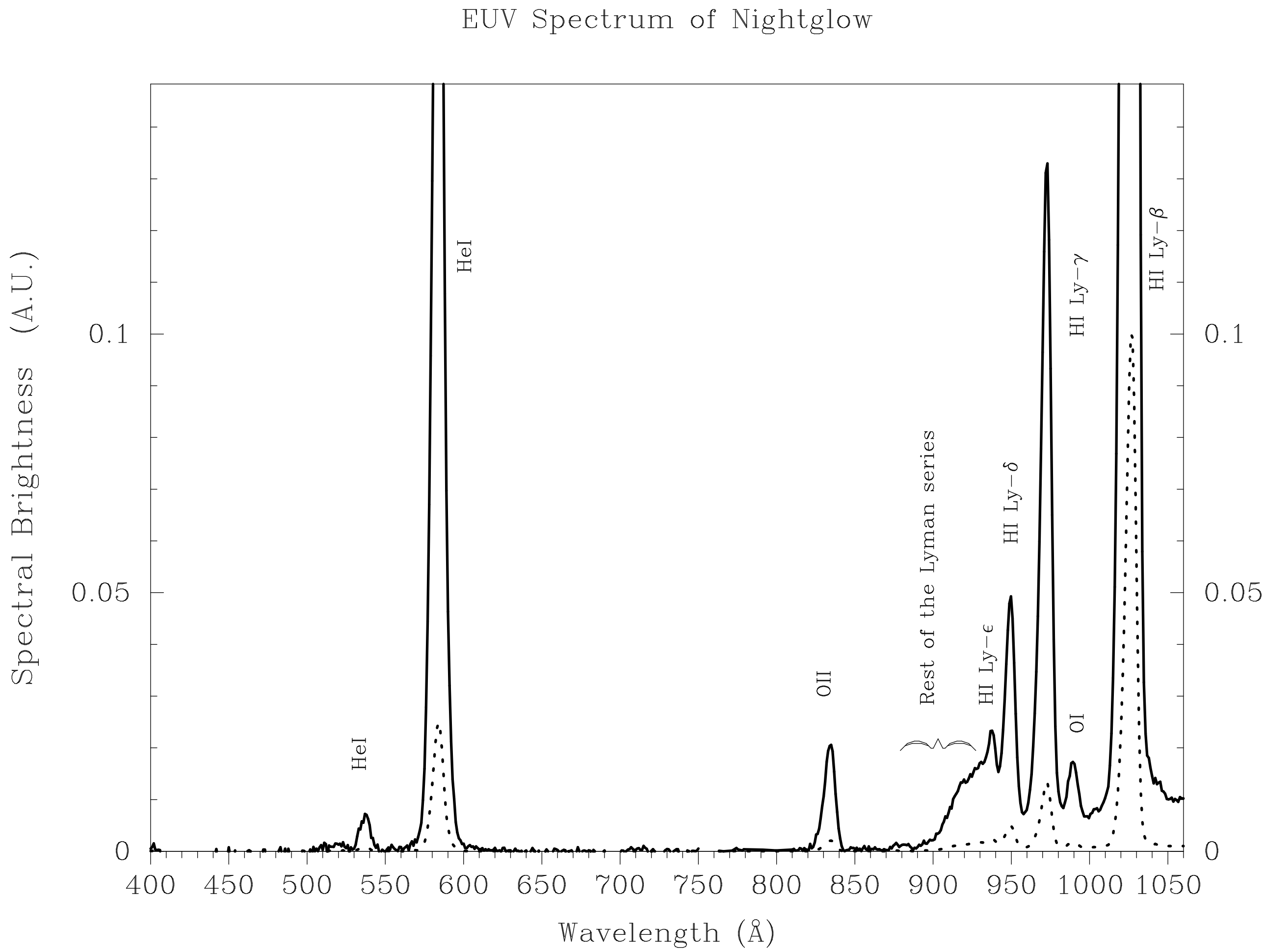

Figure 1. Solid line is the spectrum from 400 to 1060 Å obtained by EURD after ∼ 600,000 seconds of integration. Dotted line: spectrum divided by 10 to fit into the frame. The brightness scale is in arbitrary units. The measurements are taken in nighttime along a range of zenith angles of the line of sight between 0° and 85°.

an accurate determination of the expected backgrounds (primarily internally scattered hydrogen Lyman α 1216 Å radiation and detector background). The detector is surrounded by an anticoincidence shield that allows for the identification and rejection of at least 80 % of the energetic particles penetrating the detector.

EURD is 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 reported here are centered at orbital midnight time, with the line of sight towards the Earth's shadow cone, and cover a zenith angle range from −85° (atmosphere just before ground dawn) to +80° (just after dusk).

EURD observes successively with each filter (open, closed and magnesium fluoride) for periods of time of 30s:15s:45s, respectively. The closed and magnesium fluoride filters are used to remove the detector internal background and internally scattered hydrogen Lyman α 1216 Å radiation respectively [*Bowyer et al.*, 1997]. The data analyzed in this paper include a total integration time of 609874 seconds (204337 of which were of observation in the "open" filter mode) for the long wavelength spectrograph, and 604224 seconds (203521 seconds "open") for the short wavelength one.

Results and discussions

In Figure 1 it is shown the integrated line emission for the airglow spectrum obtained with both spectrographs. The lines we have unambiguously identified are listed in Table 1. The fluxes given in this table are estimated to be accurate to

Table 1. Nightglow lines identified with EURD

Wavelength (Å)	Identification	Integrated flux[a] (R) (Z.A. 0°-85°)
537	HeI Lyman β	0.01
584	HeI Lyman α	7×10^{-1}
834	OII	5×10^{-2}
937	HI Lyman ϵ	4×10^{-2}
949	HI Lyman δ	10×10^{-2}
972	HI Lyman γ	3×10^{-1}
989	OI	2×10^{-2}
1025	HI Lyman β	2.5

[a]The line fluxes given in this table are estimated to be accurate to 50 %, based on ground calibration.

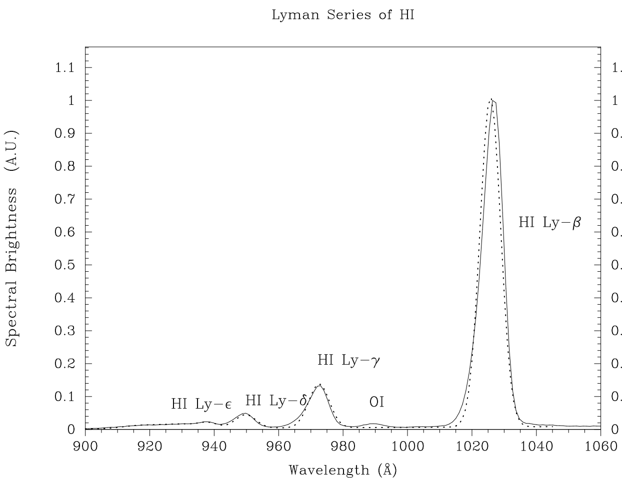

Figure 2. Lyman series of atomic hydrogen as observed by EURD (solid line) and calculated for a temperature of 5750 K (dotted line).

50 %, based on ground calibration. The comparison of the line intensities between the different previous experiments is not straightforward due to the different zenith angle ranges of the observations. It can be seen that we have detected and resolved the Lyman series lines of geocoronal atomic hydrogen, from Lyman β to Lyman ϵ. We identify the emission between 912 and 938 Å as the rest of the Lyman series which is blended given the spectral resolution of the instrument.

To confirm these identifications, we show in Figure 2 the spectrum in this wavelength region, compared with a simple model of the expected emission from the Lyman series, smoothed to simulate the spectral resolution of EURD. The synthetic spectrum has been calculated by considering that the different electronic levels are populated by following the Boltzmann distribution:

$$\frac{N_k}{N_i} = \frac{g_k}{g_i} \exp\left(-\frac{w_k - w_i}{kT}\right)$$

and that the emission is proportional to the Einstein coefficient for spontaneous emission:

$$I_{ki} \propto A_{ki} N_k$$

The best fit of the synthetic spectrum to the observed one is obtained for a temperature of 5750 K, this is in accordance with the results obtained by *Chamberlain* [1995].

Meier [1995] [1996] analyzed in detail the Lyman series of the atomic hydrogen from a high resolution solar spectrum taken from a rocket borne spectrograph. He was able to resolve up to Lyman-11 in the solar spectrum and to derive the emission g-factors for the complete Lyman series by developing a model for the excitation of the lines that also includes cascading from upper states. In absence of extinction or multiple scattering the ratios between these g-factors so calculated should equal the ratios between the emission of the lines in the atmosphere. They obtained a value of 7.1 for the ratio Lyman β/Lyman γ, of 5.2 for the ratio Lyman γ/Lyman δ and of 3.6 for the ratio Lyman δ/Lyman ϵ. Our experimental results give respectively the values of 8.2, 3.1 and 2.5 that do not significantly differ form the calculated values of Meier, considering that the spectrum presented in

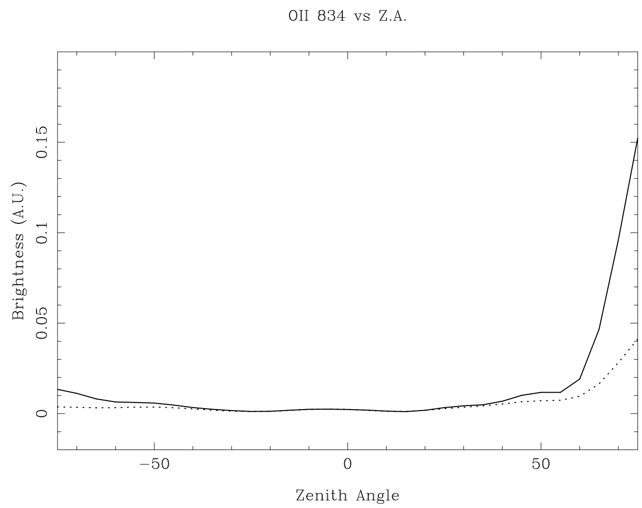

Figure 3. Emission versus zenith angle of OII line at 834 Å measured by EURD (solid line), and emission corrected from the effect of the different path along the emission region (dotted line).

this paper has been obtained during a long period and under different observational geometries.

We have clearly detected two lines of the Lyman series of helium. In principle, the identification of the line at 537 Å as helium Lyman β may be ambiguous, since there is also an OII line expected at this wavelength, but the presence in the spectrum of the rest of the Lyman series (in particular Lyman γ and δ at 522 and 515 Å), especially at largest zenith angles, makes the identification of this 537 Å feature more reliable.

Although with a lower spectral resolution, *Jelinsky et al.* [1995] identified the feature at 537 Å as from HeI. The 584/537 ratio obtained by them was of the order of 30. With EURD we have measured a ratio of 36, in agreement with Jelinsky et al's result. If in the 537 Å feature were included

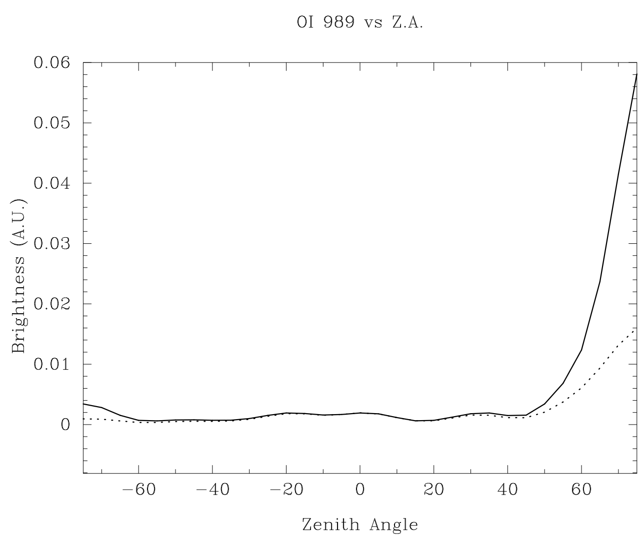

Figure 4. Emission versus zenith angle of OI line at 989 Å measured by EURD (solid line), and emission corrected from the effect of the different path along the emission region (dotted line).

a significant fraction of OII, the ratio should decrease, opposite to our observations.

Emission of OII at 834 Å, thought to be resonantly scattered solar emission from plasmaspheric oxygen ions [*Chakrabarti et al.*, 1984], is clearly detected in our measurements. The plot of emission versus zenith angle is shown in Figure 3 and shows that there is an asymmetric behavior of the emission with respect to the transit by the local meridian. In this figure we show both the emission measured versus zenith angle and the emission corrected of the effect of the different path along the line of sight through the emission region (i.e. multiplied by the cosine of the zenith angle). There is a noticeable increase of the signal when the satellite approaches the end of the eclipse and begins to observe regions that have been recently illuminated by the Sun. The fact that the emission from this "recently heated" atmosphere is clearly different than the one observed at the same geometry but at the beginning of the eclipse (when the atmosphere has not been illuminated by the Sun for a long time) indicates that a complex mechanism is involved in the excitation of OII and its origin cannot be directly attributed to scattering alone.

The only emission from atomic oxygen in the EURD range that is observed is the one corresponding to the transition $3s\ ^3D^0 \rightarrow 2p^4\ ^3P$ at 989 Å. The atomic oxygen transition $3d\ ^3D^0 \rightarrow 2p^4\ ^3P$ at 1027 Å is blended with the strong Lyman β line and cannot be clearly identified. *Abreu et al.* [1984] reported the first identification of the oxygen 989 A line. They studied its morphology and were able to propose dielectronic recombination as the excitation source for the emission. The behavior of the OI emission at 989 Å with zenith angle is shown in Figure 4. This emission mimics the characteristics observed in the emission of OII at 834 Å, but even more pronounced. The limb brightening along the initial part of the eclipse follows a cosine law, but when the satellite approaches the "recently heated atmosphere" there is a considerable increase in emission. We are developing a model to study the behavior of the OI and OII emissions at both eclipse limbs but it is out of the scope of the present work.

In the HUT spectrum, *Feldman et al.* [1992] observed a strong feature at 911 Å corresponding to the recombination continuum of atomic oxygen (e^- recombined with O^+). This feature is observed as the dominant feature in the 800 to 1100 Å range, even brighter than HI Lyman β. The same feature was previously observed by *Chakrabarti et al.* [1984] with a value of 1.47 R as compared to an intensity of 1.27 R for the OII emission at 834 Å. The emission at 834 Å is clearly observed with EURD with an intensity of $\sim$ 0.05 R but the emission at 911 Å is not evident. Its intensity must be sufficiently low that it cannot be resolved from the weak hydrogen Lyman series in which it should be embedded.

Since the altitude of the observations by *Feldman et al.* [1992] is 358 km which is lower than that of our instrument (575 km), we could conclude that the recombination processes giving rise to the 911 Å continuum emission occurs below 575 km. However, the observations of *Chakrabarti et al.* [1984] are taken at a similar altitude of EURD and no obvious reason has yet been found to explain why EURD does not see this feature.

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J. J. López-Moreno, Instituto de Astrofísica de Andalucía, CSIC, Camino Bajo de Huétor 24, 18008 Granada, Spain. (e-mail: lopez@iaa.es)

J. F. Gómez,C. Morales, J. Trapero, Laboratorio de Astrofísica Espacial y Física Fundamental, Apartado de Correos 50727, 28080 Madrid, Spain. (e-mail: jfg@laeff.esa.es; morales@laeff.esa.es; trapero@laeff.esa.es)

S. Bowyer, J. Edelstein, E. J. Korpela and M. Lampton, Space Sciences Laboratory, University of California, Berkeley, CA 94720-5030 (e-mail: bowyer@ssl.berkeley.edu; jerrye@ssl.berkeley.edu; korpela@ssl.berkeley.edu; mlampton@ssl.berkeley.edu)

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