

## Solar EUV Irradiance Variations: A Review

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Solar EUV irradiance plays a fundamental role in shaping the structure of the thermosphere and the ionosphere. Radiometric observations in this spectral domain are lacking since 1980. New models have been developed based upon the Solar Mesosphere Explorer (SME) Lyman alpha measurements during the declining phase of cycle 21 and the rising phase of the current cycle. This paper will review the recent results obtained in EUV irradiance studies, including solar EUV modeling, for wavelengths from the FUV H Lyman-alpha line at 121.6 nm down to the X-rays.

### 1. Introduction

The solar extreme ultraviolet (EUV) irradiance, corresponding to wavelengths below the H Lyman-alpha emission line (121.6 nm) initiates the photodissociation and the photoionization processes in the terrestrial thermosphere and ionosphere. It, therefore, plays a fundamental role in the thermal structure, the composition and the dynamics of this upper part of the atmosphere. It corresponds to emissions from the chromosphere and the corona in the solar atmosphere.

Measurements of such solar irradiance can only be performed by sounding rockets and satellites, the first giving snapshots and absolute measurements of the irradiance, the second providing, in addition, the temporal variations on various scales.

Several observations were performed during solar cycle 20. They have already been reviewed by TIMOTHY (1977) for the EUV range and by VIDAL-MADJAR (1977) for Lyman-alpha. A compilation with intercomparison of EUV and UV irradiance measurements has also been published by DELABOUDINIÈRE *et al.* (1978).

Only one satellite measurement of EUV irradiances was performed during the solar cycle 21, namely the Atmospheric Explorer-E (AE-E). The observations were reported by HINTEREGGER *et al.* (1981). They covered the ascending phase of the solar cycle 21. Lyman-alpha measurements were also performed by the Solar Mesosphere Explorer (SME) during the declining phase of solar cycle 21 and extended into the rising phase of the current cycle (BARTH *et al.*, 1990). This is the longest time series of Lyman-alpha obtained so far (7 1/2 years). The absence of any EUV observations from 1980 to 1988 was referred to as the EUV "hole" by DONNELLY (1987). A review of solar cycle 21 UV and EUV measurements has been recently published by ROTTMAN (1988).

The purpose of this work is to update this latter work by briefly reviewing the state of the art in EUV irradiance measurements including the new rocket observations and the EUV

modeling effort based upon the available proxies and the SME Lyman-alpha time series. Results of the San Marco 5 satellite are still too preliminary to be presented in this work.

## 2. Observations

### 2.1 The H Lyman-alpha emission line (121.6 nm)

Usually, for aeronomic purposes, a conventional value of  $3 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$  has been adopted for low solar activity condition. It has even been used as a minimum value (July 1976) to normalize the AE-E time series starting in 1977 although VIDAL-MADJAR and PHESSAMAY (1980) reported from the Orbiting Solar Observatory (OSO) 5 measurements a minimum value of the order of  $2.6 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ .

The last Lyman-alpha snapshot observation was made by means of the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) during the Spacelab 2 mission in August 1985 (VAN HOOSIER *et al.*, 1988) which took place near the minimum of activity between solar cycle 21 and 22. It provides an accurate value of  $3.12 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$  with an uncertainty of 3.5%, that is to say close to the conventional value adopted for minimum level of activity. This value is contradicted by the SME time series obtained from October 1988 to April 1989 and calibrated with the rocket observation performed on May 17, 1982 with an accuracy of 8% (MOUNT and ROTTMAN, 1983), giving after a 100-day smoothing by FFT technique (SIMON *et al.*, 1987) minimum values around  $2.5 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$  in 1986. Most of the observations of the 11-year variation suggests a factor of 2 variation over one solar cycle, except the AE-E time series which indicates a higher factor but which suffers of unexplained shifts in measured irradiances during its lifetime, for several solar emission lines. The AE-E data have been corrected by BOSSY and NICOLET (1982), BOSSY (1983) and OSTER (1983) by using a linear relationship with the solar 10.7 cm radio flux.

Very recently, BARTH *et al.* (1990) demonstrated from the SME time series the poor correlation of Lyman-alpha irradiance values with the solar 10.7 cm radio flux obtained during the solar minimum (Fig. 1). The correlation is better during the declining phase of solar cycle 21 and the rising phase of the current cycle but with different constant of proportionality for the two periods. Another study based upon the correlation of the SME Lyman-alpha time series with ground based measurements of the Ca II K line was published by WHITE *et al.* (1990). It shows a strong correlation between the two measurements even

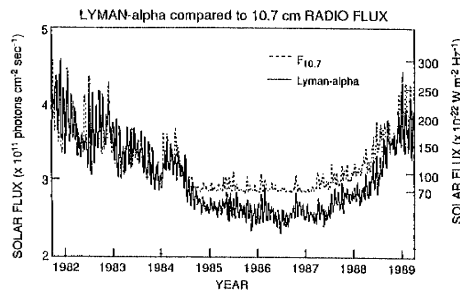


Fig. 1. Comparison of solar Lyman-alpha and 10.7 cm flux for October 11, 1981–April 13, 1989. From BARTH *et al.* (1990).

during the solar minimum. The estimated maximum values computed from the Ca II K line relationship are in average around  $4 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$  for the previous solar maximum and in 1989.

The minimum value around  $2.5 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$  and a solar cycle variation of about a factor of 1.6 deduced from the SME data are supported by the previous minimum value reported by VIDAL-MADJAR and PHISSAMAY (1980) and by the data obtained by the Pioneer Venus Orbiter suggesting a minimum value of  $2.4 \times 10^{11} \text{ hv}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$  and a solar cycle variation of 1.8 (AJELLO *et al.*, 1987).

## 2.2 The EUV domain (10 nm to Lyman-alpha)

The various rocket and satellite observations made during solar cycle 20, between March 1967 and September 1975 provided absolute values with large uncertainties (up to 35%) and with important discrepancies which make reliable analysis of long term variation difficult. Despite this fact, HINTEREGGER (1976) quoted a solar cycle variation of EUV irradiances of 30%, based upon a careful analysis of the available rocket data sets. If the minimum value seemed adequate to explain the structure and the composition of the thermosphere and the ionosphere, the variation of 30% from minimum to maximum activity levels was inadequate to model the behavior of this region of the terrestrial atmosphere which required a factor 2 in the solar cycle variation (see for instance ROBLE, 1976).

This problem was solved with the AE-E EUV observations covering the spectral range 14–105 nm from July 1, 1977 to December 31, 1980, corresponding to the rising phase of solar cycle 21. The satellite data were calibrated by means of a rocket-borne experiment performed on April 23, 1974 by HEROUX and HINTEREGGER (1978), corresponding to minimum levels of solar activity, comparable to those obtained in July 1976 according to the 10.7 cm radio flux. A reference spectrum for low activity level was published by HINTEREGGER *et al.* (1981) and archived in the NSSDC with the label SC#21REFW. A second rocket flight, reported by TORR and TORR (1985), was performed on August 14, 1979 and was used to calibrate the AE-E data corresponding to maximum activity levels of solar cycle 21.

The highest irradiance data were obtained earlier, on February 19, 1979, and the ratio with the reference spectrum adopted for July 1976 gives between 2 and 3 for the chromospheric emissions lines and above 4 for coronal fluxes (see Fig. 3 in ROTTMAN, 1988 and Table 2.4 in TOBISKA, 1990).

For aeronomic purposes, the EUV solar spectrum was divided in 37 intervals by TORR *et al.* (1979) and HINTEREGGER (1981). Fifteen wavelength intervals or discrete lines in the EUV were detailed in that time series and an empirical model was proposed by HINTEREGGER *et al.* (1981) in order to provide irradiance values for the both missing times as well as the additional EUV irradiances. Discussion of this model is presented below as SERF1.

Two sounding rocket experiments performed on November 10, 1988 and June 20, 1989 provided the first narrow band solar EUV irradiance measurements since the end of 1980 (WOODS and ROTTMAN, 1990; WOODS, private communication 1990). The two spectrometers were calibrated against the Synchrotron Ultraviolet Radiation Facility (SURF2) at NIST, giving uncertainties on the irradiance values between 8 and 15% in the range of 30–105 nm.

The first rocket observation (Fig. 2) was made during the lifetime of the San Marco 5 satellite and will be used to calibrate the EUV channels of the Airglow-Solar Spectrometer Instrument (ASSI). This latter instrument made solar EUV irradiance measurements from

March to December 1988. The data analysis is in progress. Only preliminary results are available and are not appropriate for this review.

### 2.3 The soft-X ray domain (2 to 10 nm)

The measurements of solar irradiance below 10 nm have recently been reanalyzed by FENG *et al.* (1989). This wavelength range is responsible for the enhancement of the solar activity variation of nitric oxide in the E region of the ionosphere as recently discussed by BARTH *et al.* (1988). A composite spectrum from 2 to 57.5 nm has been proposed, by FENG *et al.* (1989) based upon sounding rocket and satellite observations performed over the past two decades, in order to compare the recent rare gas ionization cell measurements obtained in

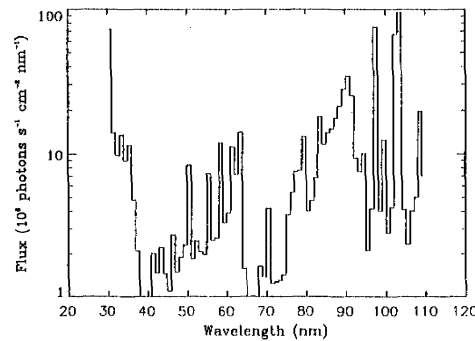


Fig. 2. The full-disk solar EUV flux on November 10, 1988 in 1 nm bins. The solid line is the total solar EUV flux and the dashed line is the continuum flux without the 21 brighter solar emissions lines. From WOODS and ROTTMAN (1990).

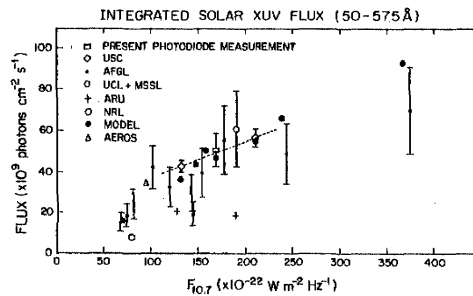


Fig. 3. The total integrated solar EUV flux between 5.0–57.5 nm as shown by OGAWA *et al.* (1990). Organizations which made individual rocket measurements are described in that reference. The USC data have the lowest uncertainty and are denoted by a diamond and a box (USC and “present photodiode measurement”). The model values for a variety of levels of solar activity, as indicated by 10.7 cm flux in the abscissa, are shown as filled circles with no error bars. An additional data point has been added with the AEROS A satellite measurement on January 19, 1973 when 10.7 cm flux = 95 which had an integrated flux of  $34.6 \times 10^9 \text{ hv} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \pm 20\%$  described by SCHMIDTKE (1976).

August 1982 and 1983 (CARLSON *et al.*, 1984; OGAWA and JUDGE, 1986) with previous spectral measurements obtained at wavelengths below 10 nm. More recently, OGAWA *et al.* (1990) published a new measurement (Fig. 3) utilizing a silicon photodiode with a quoted accuracy of 14%, which confirms the solar cycle variation of integrated irradiance between 5 and 57.5 nm by a factor of 2 to 3. For the soft X-ray region, solar cycle variation can be as much as a factor 3 to 5. (FENG *et al.*, 1989).

### 3. Solar EUV Empirical Modeling

The requirement for an accurate estimate of solar EUV irradiance is based upon the effort to provide a self-consistent model of the ionospheric and neutral atmosphere composition and temperature structure which compares favorably with in situ and remotely sensed measurements. This effort to understand the energy balance in the thermosphere has produced a stream of activity over the past three decades to model the solar EUV irradiance variations. Three distinct periods in empirical solar EUV modeling can be summarized as (1) data collection and morphology description, (2) proxy correlation, and (3) model refinement.

#### 3.1 Data collection and morphology description (1937–1980)

Prior to the era of measurements of solar EUV irradiance above the atmosphere, the first empirical EUV model was proposed by SAHA (1937). He made the suggestion that an “ultraviolet excess factor” of  $1 \times 10^6$  could account for the EUV flux needed to maintain the ionization in the upper atmosphere when compared to the theoretical EUV flux calculated from a solar black body radiating at 6500 K. However, it wasn’t until successful sounding rocket flights were made above the atmosphere that solar EUV observations were actually taken. As discussed above, TIMOTHY (1977) has reviewed the history of observations from 30–120 nm through the mid 1970’s, LEAN (1987) and ROTTMAN (1988) have reviewed EUV observations from 10–120 nm through the mid 1980’s, and FENG *et al.* (1989) have provided a useful intercomparison of the integrated flux between 2–10 nm and 5–57.5 nm from many rocket observations.

The first comprehensive review of solar EUV modeling was conducted by SCHMIDTKE (1984) and covered the period through the early 1980’s. A brief synopsis of this period of data collection and solar EUV morphology description is described here. Following a successful rocket observation of a broad EUV spectrum in 1963, HINTEREGGER *et al.* (1965) tabulated an EUV flux standard for quiet solar conditions. The early results were later revised and corrected, leading to a spectrum for “medium” solar activity with nonflaring conditions as described by HINTEREGGER (1970). This was followed by the compilation of DONNELLY and POPE (1973) of an EUV model spectrum for moderate solar activity which summarized the successful observations up to the early 1970’s. Moderate solar activity was defined as solar conditions when the 10.7 cm radio flux was  $150 \times 10^{-22} \text{ W}\cdot\text{m}^{-2}\cdot\text{Hz}^{-1}$ . HINTEREGGER (1976) later reviewed the advances in measuring EUV irradiances following the Atmospheric Explorer-C (AE-C) mission in the mid-1970’s while HEROUX and HINTEREGGER (1978) released a revised reference spectrum for moderate solar activity based upon a detailed study of the 1974 rocket flight. ROBLE and SCHMIDTKE (1979) supplemented the EUV spectrum examples by describing a variety of typical EUV flux cases applied to aeronomical calculations for different solar conditions.



SERF1 and SERF2 were compared by LEAN (1990) over timescales of the 27-day solar rotation and the 11-year solar cycle. Significant differences were found between the models and between each model and the datasets upon which each was based. The differences appeared in the estimation of absolute intensities, the magnitude of peak-to-valley variation of irradiance due to solar rotation, and the maximum to minimum flux values over the 11-year cycle. The conclusion of the LEAN study indicated neither models nor measurements yet provided a consistent picture of long-term variability in the EUV portion of the Sun's spectrum.

In general, this period concluded with the important advances that models now used multiple indices to represent emissions from different solar atmospheric layers, the modeled flux values were available on a daily basis, and the models extended through the 1980's when intensive campaigns were mounted to study the energetics of the terrestrial atmosphere while actual measurements were largely unavailable. H Lyman-alpha was found to be a good full-disk index for chromospheric emission and 10.7 cm flux daily and 81-day mean values were found to be good indices for transition region and coronal emissions. However, other potential indices cannot be ruled out either. The weaknesses in the first four solar EUV models of this period primarily emerged through inconsistencies between model and observational data values and were a combined result of inadequate long-term data availability and limitations in modeling techniques and proxies. However, DONNELLY (private communication, 1990) has also noted that SERF1, 2 and 3 concentrated on relative temporal variations rather than absolute fluxes. He has indicated that all measurements and modeling used in SERF1, 2 and 3 were full disk values and no comparisons with spatially resolved solar measurements have yet been made. Also, importantly, no atmospheric evaluations of these temporal flux models were completed.

### 3.3 Model refinement (1990–1995)

Following the termination of the SERF program with the end of WITS on December 31, 1989, much of the international collaborative effort to study long-term changes in the solar and spectral irradiance has been centered in the Solar Electromagnetic Radiation Study 22 (SOLERS22). The SOLERS22 program is formally a project of the Solar-Terrestrial Energy Program (STEP) also under the auspices of SCOSTEP (1990). Within SOLERS22, two questions have been posed: "What are the daily flux values of the solar spectral irradiance in the X-ray, EUV, UV, visible and infrared wavelength ranges and the total solar irradiance?" and "What evolving solar spatial structures cause the temporal variations of these full-disk fluxes?" One objective in the project is to develop improved solar flux models for the irradiance variations.

Within this context, a sixth solar EUV flux model has recently been developed separate from the SERF3 model work. This new model, developed by TOBISKA (1991) to assist in the evaluation of the San Marco ASSI, represents an advance over the previous SERF1 and SERF2 EUV models in the areas of proxy use, modeling technique, consistency of model results with datasets and length of time modeled. The model extends from 1947 to the present for coronal EUV full-disk irradiances and from 1976 to the present for chromospheric EUV full-disk irradiances. The solar H Lyman-alpha (121.6 nm) and He I 1083 nm equivalent width (EW) measurements are used as the independent model parameters for the chromospheric irradiances while the 10.7 cm flux daily and 81-day running mean values are the independent parameters for the coronal and transition region irradiances. The results of the model give full-disk photon fluxes at 1 AU for 39 EUV wavelength groups and discrete lines