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Solar EUV Irradiance Variations: A Review

Paul C. SIMON[1] and W. Kent TOBISKA[2]

[1]*Institut d'Aéronomie Spatiale de Belgique, 3 av. Circulaire, B-1180 Brussels, Belgium*
[2]*Space Sciences Laboratory, University of California, Berkeley, 94720 California, U.S.A.*

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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 3×10^{11} hv·s^{-1}·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 PHISSAMAY (1980) reported from the Orbiting Solar Observatory (OSO) 5 measurements a minimum value of the order of 2.6×10^{11} hv·s^{-1}·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 3.12×10^{11} hv·s^{-1}·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 2.5×10^{11} hv·s^{-1}·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 emision 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 measurments even

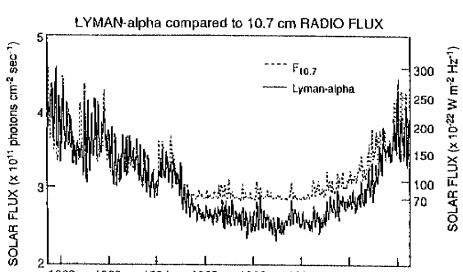

Fig. 1. Comparison of solar Lyman-alpha and 10.7 cm flux for October 11, 1981–April 13, 1989. From BARTH *et al.* (1990).

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

The minimum value around 2.5×10^{11} hv·s^{-1}·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 2.4×10^{11} hv·s^{-1}·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

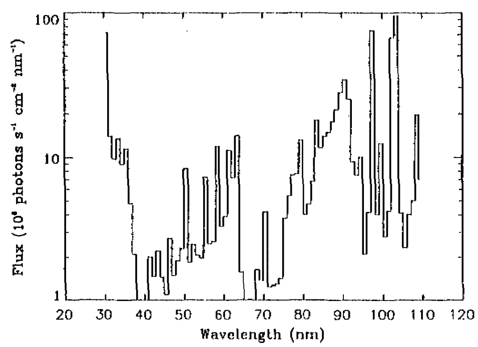

Fig. 2. The full-disk solar EUV flux on November 10, 1988 in 1 nm bins. The solid line is the total solar EUV flux and the dashed line is the continuum flux without the 21 brighter solar emissions lines. From WOODS and ROTTMAN (1990).

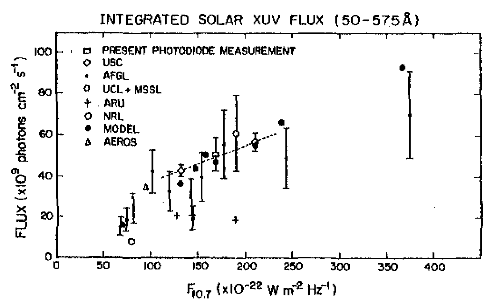

Fig. 3. The total integrated solar EUV flux between 5.0–57.5 nm as shown by OGAWA *et al.* (1990). Organizations which made individual rocket measurements are described in that reference. The USC data have the lowest uncertainty and are denoted by a diamond and a box (USC and "present photodiode measurement"). 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 34.6×10^9 $hv{\cdot}cm^{-2}{\cdot}s^{-1}$ $\pm 20\%$ 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 refinenement.

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 1×10^6 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 beteen 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 150×10^{-22} $W \cdot m^{-2} \cdot Hz^{-1}$. 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.

In retrospect, this period of EUV modeling was characterized by the collection of solar EUV spectra under a variety of solar conditions, the categorizing of quiet, moderate, and active solar condition spectra, and the description of the primary morphological features of this radiation. These features included the observations that most solar EUV irradiances varied with a 27-day period corresponding to solar rotation combined with active region evolution and had a peak-to-valley ratio of ±15% (TIMOTHY, 1977). In addition, the EUV irradiances varied with the 11-year solar cycle and had a maximum to minimum ratio ranging from a factor 2 to greater than 10 depending upon the wavelength (ROTTMAN, 1988). By the end of this period, it had become customary to represent solar EUV flux with the 10.7 cm flux values although TIMOTHY (1977) concluded in his review that the 10.7 cm flux is a highly unreliable indicator of the magnitude of EUV irradiance. In general, and secondary to the tremendous observational advances of the period, the primary weaknesses which still existed in solar EUV modeling were attributed to the lack of long-term daily irradiance measurements combined with limited proxy representation of the flux. Both of these lead to relative large uncertainty in daily modeled irradiance at almost any wavelength in the EUV.

3.2 Proxy correlation (1981–1989)

The first complete empirical solar EUV models were developed by HINTEREGGER *et al.* (1981) following the completion of the AE-E mission. Two empirical models emerged from this work. They included the two variable 10.7 cm flux association formula and the EUV class model. The former used both 10.7 cm flux daily and 81-day mean values in a linear correlation with AE-E EUV flux values between July 1977 and December 1980 in order to estimate EUV irradiances beyond that timeframe. This model was reviewed by SCHMIDTKE (1984) and was later designated SERF1 by the Solar Electromagnetic Radiation Flux Study group which worked under the auspices of the World Ionosphere-Thermosphere Study (WITS) organized by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) (DONNELLY, 1988). The second model, the EUV class model, was limited to the timeframe of the AE-E mission and used the chromospheric H Lyman-beta flux to estimate other chromospheric emission intensities and used the Fe XVI (33.5 nm) hot coronal line to estimate other coronal and transition region (hereafter referred to as coronal) emission intensities. These first two models were also more recently summarized by ROTTMAN (1988) and TOBISKA and BARTH (1990).

Subsequent to the SERF1 model, TOBISKA (1988) developed a two index EUV flux model based on the HINTEREGGER *et al.* (1981) EUV class model concept and the AE-E dataset. This model recognized the inherent weakness of characterizing EUV irradiance variability from several solar atmospheric layers with only the 10.7 cm flux index. Thus, it used the H Lyman-alpha to estimate the chromospheric irradiances and 0.1–0.8 nm X-rays to estimate the coronal irradiances. TOBISKA and BARTH (1990) improved this model by replacing the 0.1–0.8 X-ray index with the 10.7 cm flux daily values and by utilizing additional rocket measurements of the EUV to lower the uncertainty on the absolute irradiance values. This fourth empirical model was subsequently designated SERF2 (DONNELLY, private communication, 1989; TOBISKA and BARTH, 1990) and covered the time frame between October 1981 and April 1989. TOBISKA (1990) detailed the SERF2 model development. A fifth model, SERF3, is presently under development as an EUV class model where the Mg II (280 nm) measurements are used as a chromospheric emission index and the Fe XIV (530.3 nm) green line measurements are used as coronal emision index (DONNELLY, private communication 1990).

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 between 1.8 and 105.0 nm for a given date (Fig. 4). The OSO, AEROS, AE satellite datasets and five rocket datasets are used in the model development. This model represents the first of a series of refinements in EUV modeling. A climax to this work will be the development of a COSPAR International Reference Solar EUV Flux model by the end of the STEP program.

As part of the refinement of solar EUV irradiance models, the primary issues which must be addressed include the establishment of an extensive EUV database for model development and comparison, the improvement of modeling techniques to allow the inclusion of new datasets as well as the improved representation of the physics of the irradiance variations, and the testing of these models for self-consistency in atmospheric modeling.

In particular, long-term data throughout the EUV spectral range are needed. There have not yet been unambiguous measurements over a full solar cycle with a set of calibrated instruments and, in the satellite datasets which do exist, there are gaps within and between the datasets. During solar minimum conditions in the mid-1990's there is a need for combined ionization cell and spectrometric EUV measurements to resolve questions about the absolute integrated flux values between 5–57.5 nm. Higher spectral resolution measurements

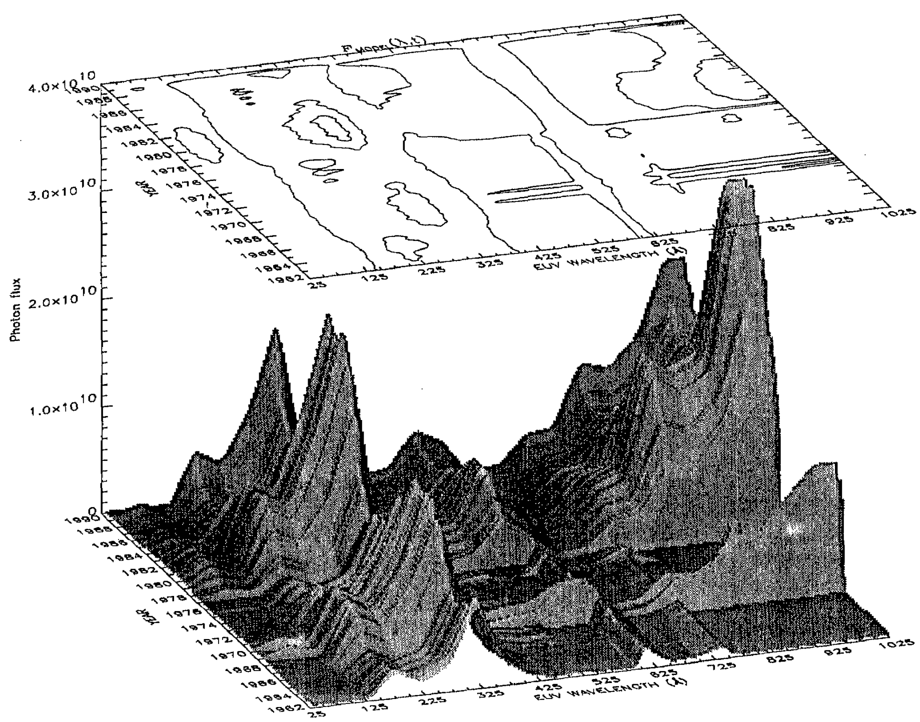

Fig. 4. Surface plot of the modeled solar EUV irradiance between 1.8–105.0 nm between January 1, 1962 and December 31, 1988. Values have been binned in 5.0 nm bins and slightly smoothed to present a quatitative estimate of photon fluxes by wavelength and time. Contour plot highlights the relative contour levels. From TOBISKA (1991).

of the full-disk emissions will allow more precise model distinctions between chromospheric and coronal lines which are spectrally close to one another (e.g. He II 30.38 nm and Si XI 30.31 nm). Finer spectral resolution will also allow for better model spectrum formats when the line shapes are compared to absorption cross sections of terrestrial atmospheric constituents. Higher spatial resolution measurements in addition to full-disk irradiance measurements will allow models to incorporate the physics of the solar atmosphere by connecting irradiance variations to spatial feature evolution and center-to-limb functions which give irradiances of different intensities from the background emission.

While contemporary solar EUV models use multiple linear regression techniques to correlate the independent (proxy) datasets with the EUV datasets, thus allowing the opportune inclusion of new proxy or EUV data as it becomes available, there may be other techniques which can be used to model the irradiance variations which have not yet been investigated. New proxy candidates for chromospheric emissions (6000–10,000 K) include space-based observations of He I (58.4 nm), He II (30.4 nm), H Lyman-beta (102.6 nm), and Mg II (280 nm) along with the ground-based observations of Ca II K plage and Ca K 1 A index. These candidates are in addition to the present H Lyman-alpha and He I 1083 nm EW proxies presently being used. New proxy candidates for transition region irradiance (>20,000 K) include space-based observations of Fe IX (16.9–17.3 nm) and Fe XI (18.0 nm). A cool coronal irradiance proxy candidate (1M K) is the space-based observation of Fe XIII (20.0–20.4 nm). Hot coronal irradiance proxy candidates (2–3M K) include the space-based 1–8 A X-rays and the Fe XV (28.4 nm) along with the ground-based coronagraph observations of the Fe XIV (530.3 nm) green line. The transition region and coronal candidates are in addition to the present 10.7 cm flux daily and 81-day mean value ground-observed data.

Atmospheric modeling, which uses modeled solar EUV irradiance as a thermospheric energy input, is extremely useful in analyzing the consistency of flux model results when the modeled atmospheric parameters are then compared with in situ measured or remotely sensed datasets. From solar maximum to minimum examples, through 27-day solar-induced variability, to daily campaign cases where the role of minor constituents and photoelectrons are analyzed, the range of applications of solar EUV modeled irradiance is wide and complex. A major goal of the STEP program is to advance the quantitative understanding of the coupling mechanisms that are responsible for the transfer of energy and mass from one region of the solar-terrestrial system to another. Solar EUV irradiance modeling will continue to be an important element of that study.

4. Summary

Solar FUV and EUV irradiance from the H Lyman-alpha line to 2 nm has been observed by satellite and rocket instruments to a limited degree during the 1980's. Lyman-alpha as measured by SME has a solar minimum value of 2.5×10^{11} hv$\cdot$s$^{-1}\cdot$cm^{-2} with a solar cycle variation of about 1.6. The 10.7 cm flux and Ca II K line comparisons with Lyman-alpha show poor to moderate correlation (10.7 cm flux during solar minimum and changing solar activity, respectively) and strong correlation (Ca II K during all solar activity).

Five sounding rockets have measured the absolute solar EUV flux in both narrow and broadband instruments since 1980. Two spectrographs were flown in 1988 and 1989 by the University of Colorado and three rare gas ionization cell or silicon photodiode instruments were flown in 1982, 1983, and 1988 by the University of Southern California. The spectral coverage of these combined instruments ranges from 2–105 nm. The San Marco ASSI instrument measured solar EUV irradiance from March to December 1988, although the data have not yet been published.

Solar EUV modeling has progressed in the 1980's by using most of the available EUV datasets. SERF1 and SERF2 were completed in the beginning and end of the decade such that estimated daily flux values between 2–105 nm are now available. New efforts which will refine previous EUV models are in progress leading to the development of a COSPAR International Reference Solar EUV Flux model through the SOLERS22 program by the mid-1990's. These new models will help advance our understanding of the fundamental coupling in the Sun-Earth system with their applications to aeronomical problems.

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