A BRIEF HISTORY OF EMPIRICAL MODELING OF THE SOLAR EUV SPECTRAL IRRADIANCE

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ABSTRACT. More than ninety years of solar extreme ultraviolet (EUV) irradiance modeling has progressed from empirical formulations, through fudge factors, to typically measured irradiances, and back to empirical models. A summary of the major modeling efforts is presented with comparisons given for selected models including Donnelly and Pope (1973), Hinteregger *et al.* (1981), and Tobiska (1991). Most models utilize the Atmosphere Explorer-E (AE-E) EUV database along with ground- and space-based proxies to create emissions from solar atmospheric regions. A useful comparison of models and several rocket datasets is given in a previously published figure of 50-575 Å integrated flux adapted with new data. Future challenges in EUV modeling are summarized, including: the basic requirements of models; the task of incorporating new observations and theory; the task of comparing models with solar-terrestrial datasets; and the long-term goals in modeling. By the late 1990s, empirical models will potentially be improved through use of real-time solar EUV images at selected wavelengths which will greatly enhance modeling and predictive capabilities.

1. INTRODUCTION

The requirement for an accurate estimate of the solar extreme ultraviolet (EUV) flux, a fundamental thermospheric energy input, has been driven by the effort to provide a self-consistent model of the ionospheric and neutral atmospheric compositional 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 considerable activity over the past three decades to model the solar EUV irradiance variations.

All empirical solar EUV models are presently limited to full-disk emissions with daily average values. The modeling of temporal and solar atmosphere or feature variation has increased the complexity of the task. The three distinct periods in empirical solar EUV modeling, summarized by Simon and Tobiska (1991), are 1) data collection and morphology description, 2) proxy correlation, and 3) model refinement. These are discussed below.

2. DATA COLLECTION AND MORPHOLOGY DESCRIPTION (1900-1980)

The first empirically modeled, time-independent, solar EUV irradiance was described on October 19, 1900 at a meeting of the Berlin Physical Society. Planck, who had been searching for a way to reconcile the Wien and Rayleigh-Jeans formulations of the spectral

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distribution of blackbody radiation, revealed to the gathering an empirical formulation which fit quite well the experimental data of the day (Planck, 1901). This function is shown in Figure 1 and is compared with the Rayleigh-Jeans and Wien's energy densities. Planck's Law,

$$u(\lambda) = \frac{8\pi hc\lambda^{-5}}{e^{hc/\lambda kT} - 1},$$

(1)

assumed that the energy of an oscillator can only take on discrete values. This formulation set the stage for the quantum theory of light and solved the "ultraviolet catastrophe." This was the term given to the infinitely increasing UV energy with shorter wavelengths in the Rayleigh-Jeans formulation.

For several decades it was expected that the solar irradiance in the EUV followed the Planck blackbody spectrum. Finally, Saha (1937) noted that the only reasonable explanation for the formation of the first negative bands of nitrogen in the night sky observed at high altitude sunrise and sunset ($z > 200$ km) was ionization from solar EUV ($\lambda < 660$). His contribution recalled that the number of photons available for N_2 ionization, according to Planck's Law, was completely insufficient given the total ion production rate
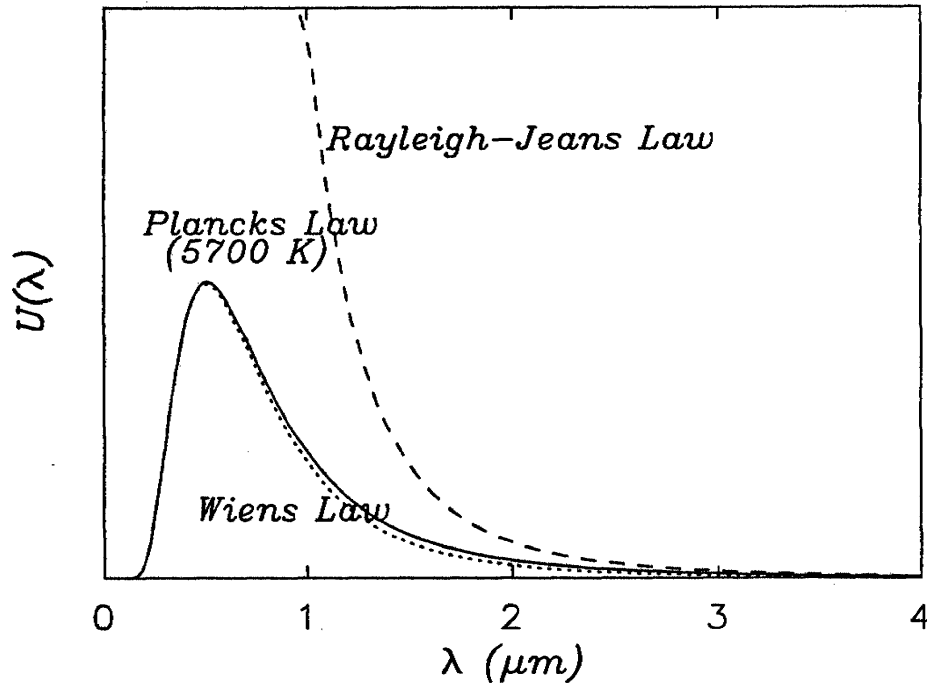

Figure 1. Comparison of blackbody radiation for Planck's Law, Wien's Law, and Rayleigh-Jeans Law. The Planck energy density spectrum fit experimental data. Relative units of $U(\lambda)$ are in energy density. This spectral distribution is for a 5700 K blackbody (e.g., the Sun).

needed to maintain Chapman's (1931) *total ionization* of 3×10^{10}. Even if only 10% of the ionization were due to N_2, Saha concluded that an "ultraviolet excess factor" of 1×10^6 more photons would be needed to maintain the ionization compared to the theoretical flux provided by a solar blackbody at 6500 K. Thus, a "fudge factor" of a million became the next de-facto EUV model.

It was not until successful sounding rocket flights were made above the atmosphere that solar EUV observations were actually taken. Figure 2 shows the solar spectrum as published by Donnelly and White (1977) as a compilation of these early observations. Timothy (1977) has reviewed the history of observations from 300 to 1200 Å through the mid-1970's, Lean (1987) and Rottman (1988) have reviewed EUV observations from 100 to 1200 Å through the mid-1980's, and Feng *et al.* (1989) have provided a useful intercomparison of the integrated flux from 20 to 100 Å and 50 to 575 Å for 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 given 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 of "medium" solar activity with nonflaring conditions (Hinteregger, 1970). This was followed by the Donnelly and Pope (1973) compilation of an EUV model spectrum for moderate solar activity which summarized the successful observations up to the early 1970's. Figure 3 shows the Donnelly and Pope spectrum where moderate solar activity was defined as solar conditions existing when the 10.7 cm radio flux, $F_{10.7}$, was 150×10^{-22} W m^{-2} 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 the detailed study of a 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.

As discussed by Simon and Tobiska (1991), 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 on larger time scales and had a peak-to-valley ratio of $\pm 15\%$ (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 of 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 $F_{10.7}$ values although Timothy (1977) concluded that the $F_{10.7}$ was 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
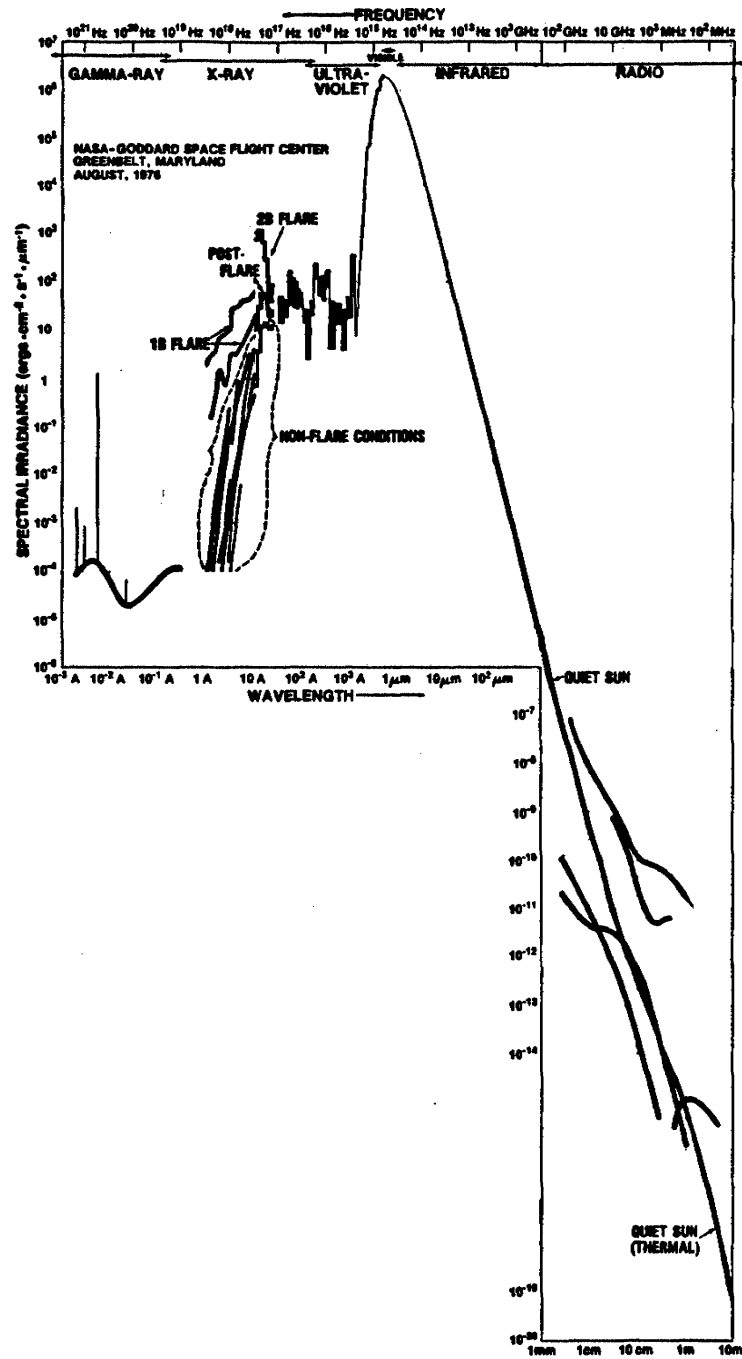
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Figure 2. The solar spectrum from gamma-rays to radio wavelengths. Reprinted from Donnelly and White (1977).
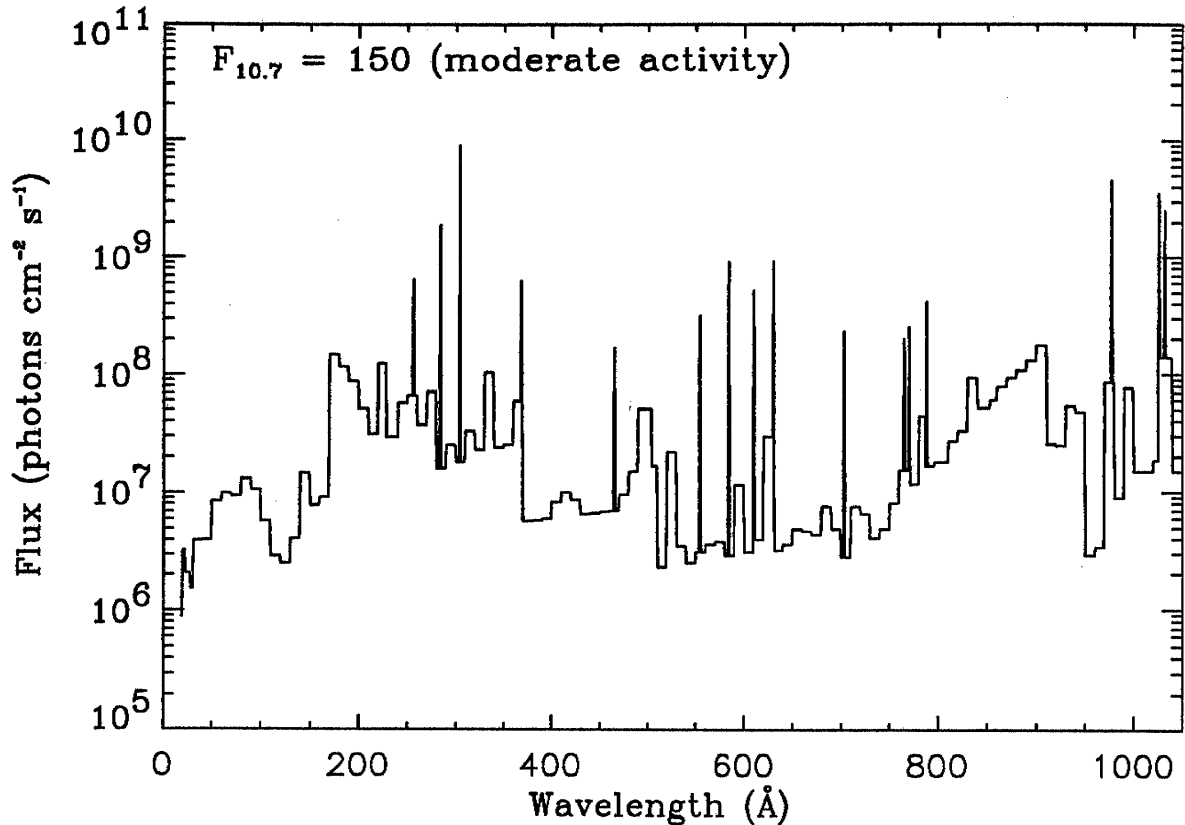
Figure 3. The Donnelly and Pope (1973) moderate solar activity spectrum compiled from several rocket observations. Several discrete lines which are the most significant EUV emission lines in terms of magnitude are shown. The remaining flux (both lines and intervals) from Table 2 in Donnelly and Pope has been binned in 10 Å bins except for emissions below 31 Å where the average bin size is 3 Å.

were attributed to the lack of long-term daily irradiance measurements combined with limited proxy representation of the flux. Both of these led to relatively large uncertainty in daily modeled irradiance at almost any wavelength in the EUV.

3. PROXY CORRELATION (1981-1989)

The first complete empirical solar EUV model was developed by Hinteregger *et al.* (1981) following the completion of the AE-E mission. A substantial contribution of this

work was the publication of the cycle 21 solar minimum reference spectrum SC#21REFW as shown in Figure 4. The model emerging from this work was composed of the EUV class model combined with a two-variable $F_{10.7}$ association formula. The EUV class model was limited to the time frame of the AE-E mission (July 1977 through December 1980) where the chromospheric H Lyman-β flux estimated other chromospheric emission intensities and the Fe XVI (335 Å) coronal line estimated other coronal and transition region (hereafter referred to as coronal) emission intensities. The irradiance values of the EUV class relationship is described in photons cm^{-2} s^{-1} by

$$I_\lambda = I_{\lambda\mathrm{ref}} + I_{\lambda\mathrm{ref}}(R_k - 1)C_\lambda \qquad (2)$$

where $I_{\lambda\mathrm{ref}}$ is the EUV flux at solar cycle minimum (Hinteregger *et al.*, 1981). R_k is the ratio for a specific date of a key EUV flux to the solar minimum value. C_λ is a wavelength-dependent scaling parameter for each EUV wavelength. The two key (k) emissions are Lyman-β and Fe XVI. The association formula used both $F_{10.7}$ daily and 81-day mean val-
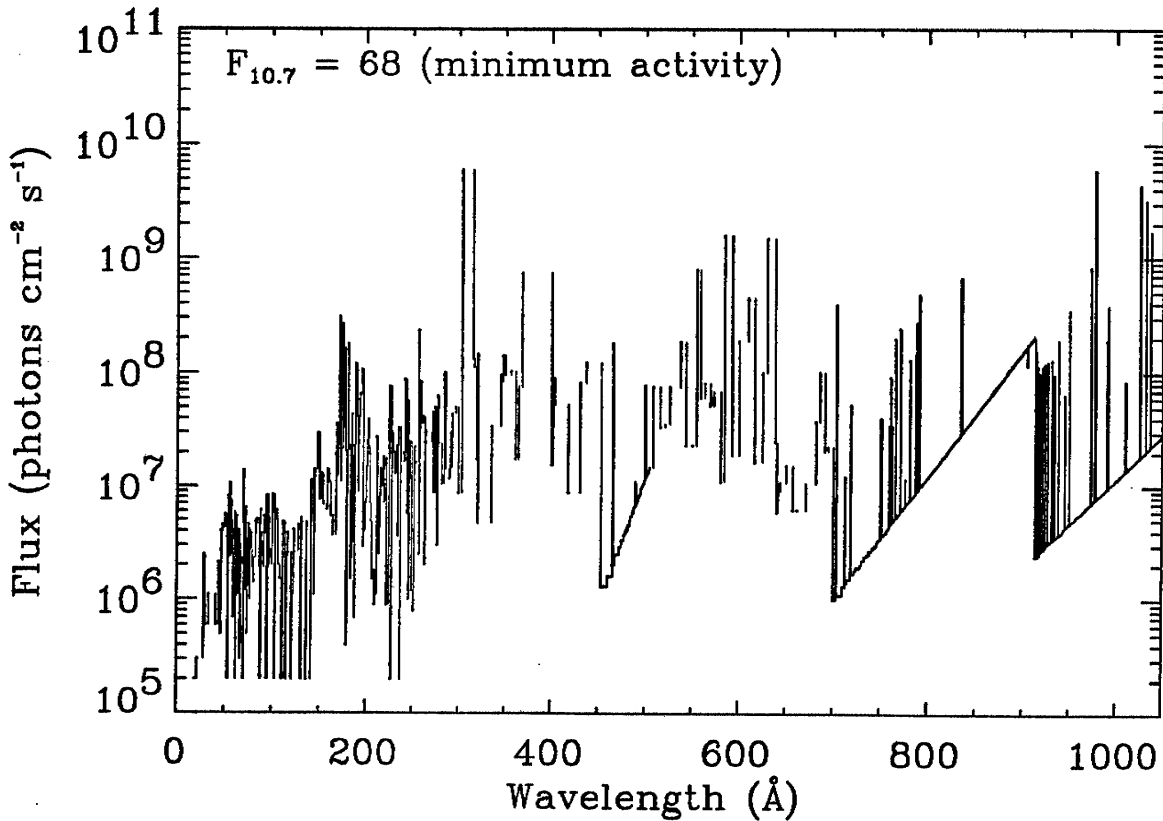

Figure 4. This spectrum represents the July 1976 period with a 1 Å wavelength grid where several wavelengths are missing. The total integrated flux from 50 to 575 Å for this spectrum is 1.5×10^{10} photons cm^{-2} s^{-1}.

ues in a linear correlation with AE-E EUV flux values in order to estimate EUV irradiances outside the AE-E time frame. This irradiance formulation is described by

$$I_\lambda = A_\lambda F_{10.7}^* + B_\lambda (F_{10.7} - F_{10.7}^*) + C_\lambda \tag{3}$$

where $F_{10.7}$ is the daily value and $F_{10.7}^*$ is the 81-day mean. A_λ, B_λ, and C_λ are obtained from a least squares fit to the AE-E EUV data. This model was reviewed by Schmidtke (1984) and more recently summarized by Rottman (1988) and Tobiska and Barth (1990). It was later designated SERF1 in the late 1980s by the Solar Electromagnetic Radiation Flux Study group under the auspices of the World Ionosphere-Thermosphere Study (WITS) organized by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) (Donnelly, 1988).

Following the release of the SERF1 model, Nusinov (1984) developed a two-component model of full-disk solar EUV irradiance variation based upon nonlinear regression formulas between $F_{10.7}$ and the AE-E EUV. Radio background and active region components were derived such that the EUV wavelengths for seven discrete lines could be modeled in a time variation. The empirically determined function which fit the $F_{10.7}$ background gave the capability of predicting this component. Figure 5 shows the Nusinov $F_{10.7}$ back-
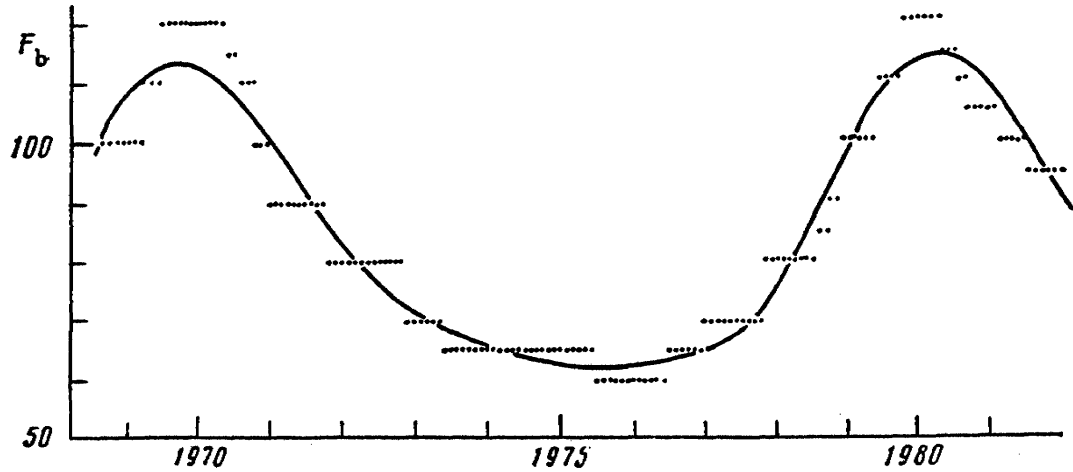

Figure 5. Nusinov (1984) provided a $F_{10.7}$ background emission representative of the chromospheric network. He determined an empirical fit to the data given in equation (5) in the text. The units of F_b are $\times 10^{-22}$ W m^{-2} Hz^{-1}. The abscissa value is time labeled with years.

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ground component (chromospheric network) and equation (4) describes his irradiance model as

$$I(\lambda) = B_0 + B_1(F_b - A)^{\frac{2}{3}} + B_2(F_{10.7} - F_b)^{\frac{2}{3}} \tag{4}$$

where the first term is the background component, the second term is the active region component, and the A, B_0, B_1, and B_2 coefficients are found in Nusinov (1984). The Nusinov background component is

$$F_b = 63 + 482\sin^{-3.7}(\pi t/T)e^{-5.2t/T} \tag{5}$$

where t is time in years from the beginning of the cycle and T is the period of the cycle, also in years. Bruevich and Nusinov (1984) extended this model throughout the EUV from 100 to 1050 Å.

The next modeling effort was by Tobiska (1988) who 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 an inherent weakness of characterizing EUV irradiance variability from several solar atmospheric layers with only the $F_{10.7}$ index. Thus, it used the H Lyman-α to estimate the chromospheric irradiances and 1-8 Å X-rays to estimate the coronal irradiances. Tobiska and Barth (1990) improved this model by replacing the 1-8 Å X-ray index with the $F_{10.7}$ daily values and by utilizing additional rocket measurements of the EUV to lower the uncertainty of the absolute irradiance values. This fourth empirical model was subsequently designated SERF2 (R.F. 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.

SERF1 and SERF2 were compared by Lean (1990) over time scales 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 solar cycle. Lean concluded that 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 important advances. Models now used multiple indices to represent emissions from different solar atmospheric layers (chromosphere or corona) or solar features (background network or active region). The modeled irradiance values were available on a daily basis (temporal variation). Finally, the models extended through the 1980s during a period when intensive campaigns were mounted to study the energetics of the terrestrial atmosphere and when actual measurements were largely unavailable. H Lyman-α was found to be a good full-disk index for chromospheric emission and $F_{10.7}$ daily and 81-day mean values were found to be acceptable indices for transition region and coronal emissions.

Weaknesses in the solar EUV models of this period resulted from some inconsistencies between model and observational data values. These were a combined result of inadequate

long-term data availability and limitations in modeling techniques and proxies. All models empirically created full-disk irradiance values at 1 AU and relied heavily on the AE-E EUV data. Donnelly (private communication, 1990) noted that SERF1 and 2 concentrated on relative temporal variations rather than absolute fluxes and that no comparisons with spatially resolved solar measurements had yet been made. In addition, no atmospheric evaluations of these temporal flux models were completed.

4. MODEL REFINEMENT (1990-1995)

The SERF program ended upon the conclusion of WITS on December 31, 1989. Since then, much of the international collaborative effort to study long-term changes in the solar total and spectral irradiance has been centered in the Solar Electromagnetic Radiation Study 22 (SOLERS22). The SOLERS22 program is a project of the Solar-Terrestrial Energy Program (STEP) also under the auspices of SCOSTEP. 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 project objective is to develop improved solar flux models for the irradiance variations. Two of these efforts are discussed here.

A fifth model, SERF3, is presently under development as a full-disk multiple proxy model for chromospheric and coronal emissions, correlating Mg II core-to-wing ratio (c/w), Ca K 1 Å index, He I 10,830 Å equivalent width (EW), $F_{10.7}$, 5303 Å, and 1-8 Å data with the AE-E dataset (R.F. Donnelly, private communication, 1991).

A sixth solar EUV flux model has recently been developed separately from the SERF3 work but also as a SERF program project. This new model (Tobiska, 1991) was developed to assist in evaluating the solar data from the San Marco Airglow Solar Spectrometer Instrument (ASSI) (Tobiska *et al.*, 1990). It represents an advance over the previous SERF1 and SERF2 EUV models in proxy use, modeling technique, and consistency of model results with datasets. 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-α (1216 Å) and He I 10,830 Å EW measurements are used as the independent model parameters for the chromospheric irradiances while the $F_{10.7}$ 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 18 and 1050 Å for a given date. Data from the OSO1/3/4/6, AEROS A, AE-E satellites and six rocket datasets are used in the model development. The irradiance from this model is given as

$$\Phi(\lambda, t) = a_0(\lambda) + \sum_{i=1}^{4} a_i(\lambda) F_i(t) \tag{6}$$

$F_i(t)$ $(i = 0, 1, \cdots, 4)$ are the proxy datasets where $F_1(t)$ is Lyman-α, $F_2(t)$ is He I 10,830 Å EW scaled to Lyman-α values, $F_3(t)$ is daily $F_{10.7}$, and $F_4(t)$ is the 81-day running mean

value of $F_{10.7}$. The other coefficients of $a_i(\lambda)$ are given in Tobiska (1991). Missing proxy data are substituted through an empirical relationship with another proxy for which data do exist on given dates. Figure 6 shows three examples of this model under low, moderate, and high solar activity conditions on the same wavelength scale as SC#21REFW. Figure 7, adapted from Ogawa *et al.* (1990), shows a comparison of the model with several rocket flights and two previous models, i.e., those of Donnelly and Pope (1973) and SC#21REFW (Hinteregger *et al.*, 1981), for the 50-575 Å integrated flux.

5. ISSUES AND GOALS OF MODEL DEVELOPMENT

The basic requirements for present full-disk empirical model refinements include: 1) wavelengths (discrete lines and intervals) compatible with community requirements; 2) consistency between model results and datasets used to derive a model for all periods of solar activity; 3) reproduction of solar cycle (11-year) magnitude, phase, rise, and decline; 4) reproduction of solar rotation (27-day) magnitude and phase; 5) reproduction of emissions from atmospheric regions and features; 6) continuum and line shape consistency with physics; and 7) user-friendly model application to special cases (solar minimum, maximum, campaign dates, etc.).

A culmination of the present refinement stage of empirical modeling will be the development of a time-dependent, full-disk COSPAR International Reference Solar EUV irradiance model by the end of STEP. This is in line with international aeronomy community efforts to reduce the uncertainty in thermospheric and ionospheric modeling. This atmospheric modeling often requires full-disk, daily irradiance values at 1 AU for at least fifteen important lines and two dozen wavelength intervals between 18 and 1050 Å.

As part of the refinement of solar EUV irradiance models, critical 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, the improved representation of the physics of irradiance variations for line versus continuum emission, and the testing of these models for self-consistency in atmospheric modeling.

In particular, long-term data with high spectral and spatial resolution throughout the EUV spectral range are needed. There have not yet been unambiguous measurements over a full solar cycle with a set of calibrated or intercalibrated instruments and, in the satellite datasets which do exist, there are gaps within and between the datasets. During solar minimum conditions in the mid-1990s, there is an acute need for combined ionization cell and spectrographic EUV measurements in order to resolve a question regarding the absolute integrated flux values between 50 and 575 Å. Higher spectral resolution measurements of the full-disk emissions will allow more precise distinctions between chromospheric and coronal lines which are spectrally close to one another (e.g., He II 303.78 Å and Si XI 303.31 Å) and will also allow differentiation between the line shape from the underlying continuum. Finer spectral resolution will also result in spectrum formats with highly
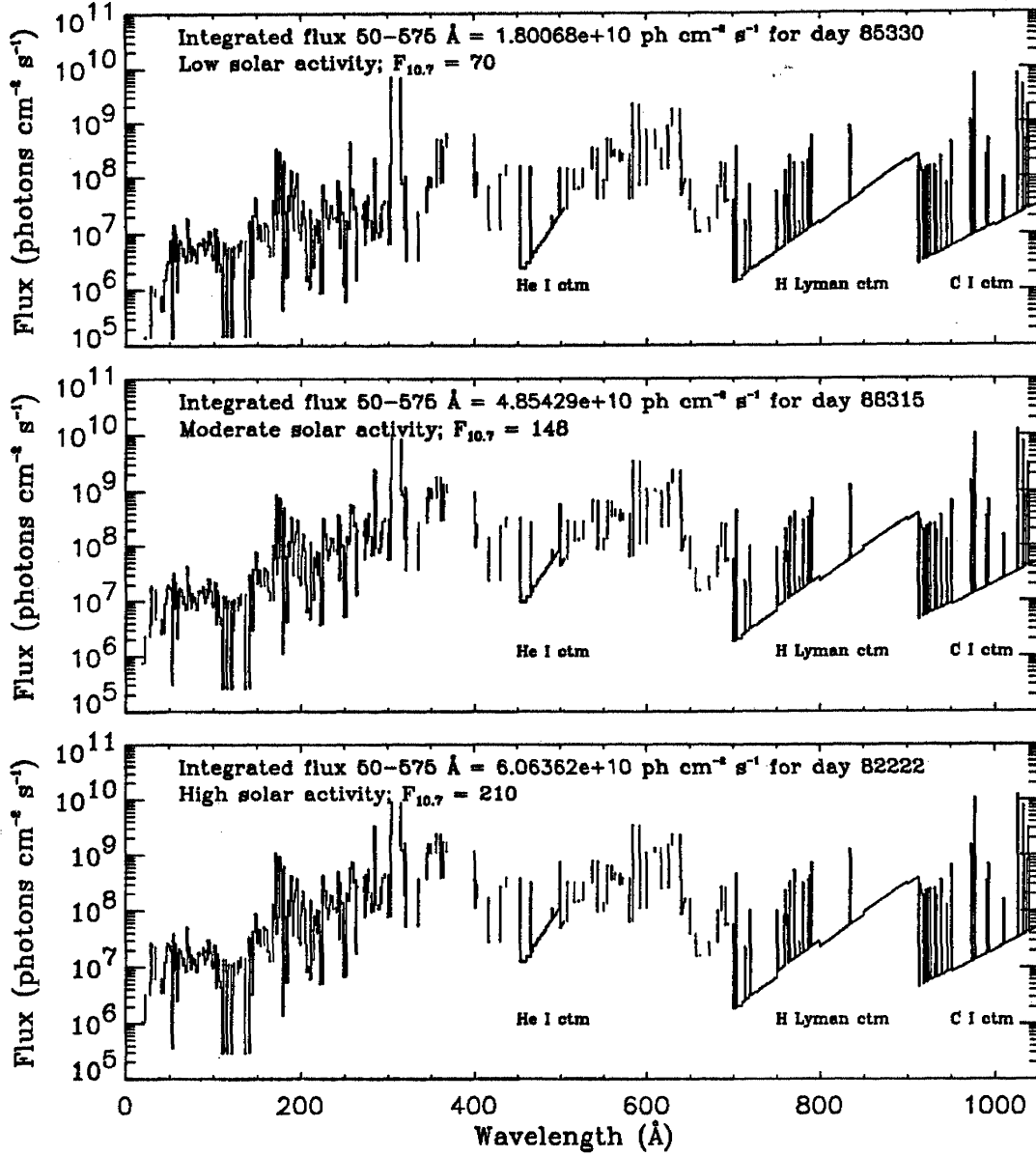
Figure 6. The Tobiska (1991) model solar EUV spectrum for November 26, 1985 (low solar activity), for November 10, 1988 (moderate activity), and for August 10, 1982 (high activity) are shown in three panels. The total integrated flux for 50 to 575 Å is 18.0×10^9 photons cm^{-2} s^{-1} for the November 1985 case, 48.5×10^9 photons cm^{-2} s^{-1} for the November 1988 case, and 60.6×10^9 photons cm^{-2} s^{-1} for the August 1982 case. The He I continuum is visible between 450 and 504 Å, the H Lyman continuum is between 700 and 912 Å, and the C I continuum is between 913 and 1050 Å in each panel. Discrete emission lines rise considerably higher than the continua. The modeled spectrum is based on the wavelength ranges of the SC#21REFW spectrum and contains missing lines.
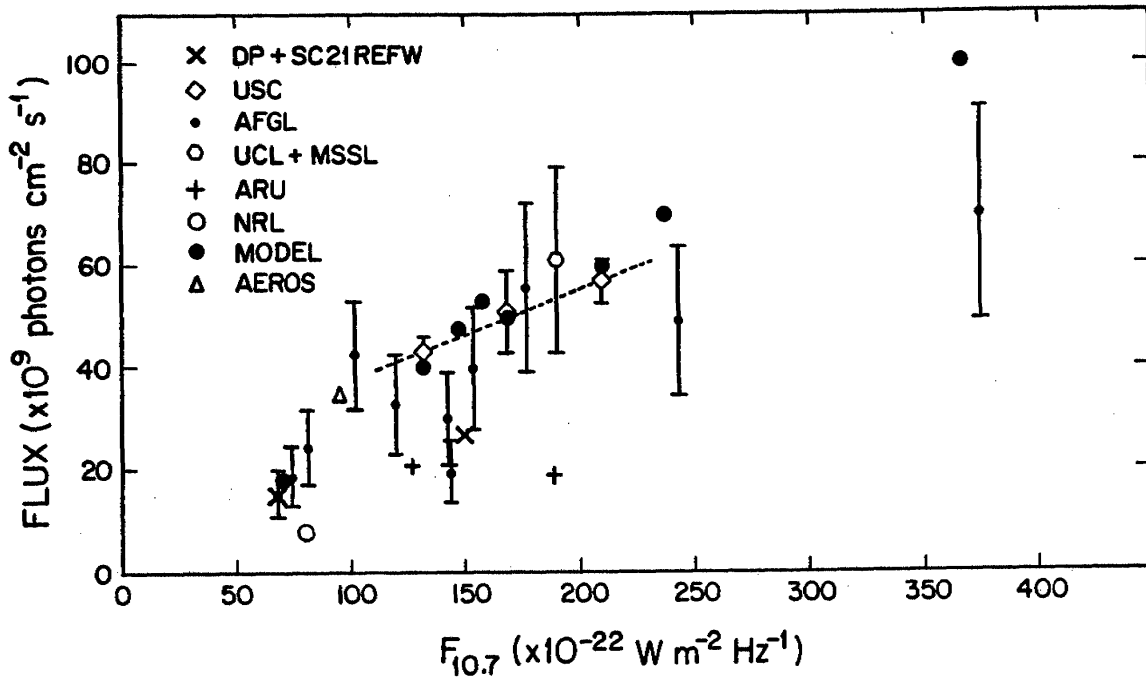
Figure 7. The total integrated solar EUV flux from 50 to 575 Å adapted from Ogawa et al. (1990). Organizations which made individual rocket measurements are described in that reference. The USC data have the lowest uncertainty and are denoted by diamonds. The model values for a variety of levels of solar activity, as indicated by $F_{10.7}$ in the abscissa, are shown as filled circles with no error bars. Additional data points have been added with 1) the AEROS A satellite measurement on January 19, 1973, when $F_{10.7} = 95$, which had an integrated flux of $34.6 \times 10^9 \pm 20\%$ described by Schmidtke (1976), and 2) the Donnelly and Pope (1973) (DP) and SC#21REFW spectra denoted by X. The integrated fluxes for those two spectra are 26.9×10^9 ($F_{10.7} = 150$) and 15.0×10^9 ($F_{10.7} = 68$), respectively.

defined line binning which will be useful with better-known absorption cross sections of atmospheric constituents for calculating more accurate ionization frequencies.

Empirical modeling with higher spatial resolution, which will directly improve our understanding of solar physics, will be an outgrowth of improvements in imaging technology. Data for such modeling might be available from several experiments ranging from Skylab solar images to the planned Coronal Diagnostic Spectrometer on the SOHO satellite and the Solar X-ray Imager on the GOES L satellite in the late 1990s. Higher spatial resolution will allow models to incorporate the physics of the solar atmosphere by connecting irradiance variations to solar feature evolution (e.g., active regions, network emission, loops, and holes) and to center-to-limb functions which give irradiances different from the background or full-disk emission. "Climatological" empirical irradiances will be possible with spatial

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data and will assist our understanding of the small- and medium-scale dynamics of the solar subsurface, photosphere, and atmospheric layers based upon their deviations from the solar climatological norms.

Whereas contemporary solar EUV models use mulitiple 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 they become available, there may be other techniques for modeling the irradiance variations which have not yet been investigated. Nusinov's (1984) nonlinear regression formulas provide an important step in this direction.

New proxy candidates for chromospheric emissions (6000-10,000 K) include space-based observations of He I (584 Å), He II (304 Å if it can be resolved from the Si XI line), and Mg II (c/w) along with the ground-based observations of Ca II K plage and Ca K 1 Å index. These candidates are in addition to the H Lyman-α and He I 10,830 Å EW proxies presently being used. New proxy candidates for transition region irradiance ($> 20,000$ K) include space-based observations of Fe IX (169-173 Å) and Fe XI (180 Å). A cool coronal irradiance proxy candidate (1M K) is the space-based observation of Fe XIII (200-204 Å). Hot coronal irradiance proxy candidates (2-3M K) include the space-based 1-8 Å X-rays and the Fe XV (284 Å) along with the ground-based coronagraph observations of the Fe XIV (5303 Å) green line. The transition region and coronal candidates are in addition to the present $F_{10.7}$ daily and 81-day mean value ground-observed data. Donnelly (private communication, 1991) has indicated that SERF3 will take advantage of a number of these new proxies.

Important improvements in future empirical models will incorporate more physical processes into the temporal irradiance variations. Immediate improvements, for example, could be made in 1) providing a solar blackbody continuum which underlies the line emission and may be important for those parts of the spectrum where few lines are prominent; 2) providing a physical basis for the He I, H Lyman, and C I continuum slopes and magnitudes; and 3) distinguishing the monochromatic line shapes and refining the binning based upon line centers and line widths for important emissions.

Atmospheric modeling, which uses solar EUV irradiance as a thermospheric energy input, is extremely useful in analyzing the consistency of irradiance model results when the calculated atmospheric parameters are compared with in situ measured or remotely sensed datasets. From solar maximum to minimum examples, through 27-day solar-rotation 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 current major goal of STEP is to advance the quantitative understanding of the coupling mechanisms responsible for the transfer of energy and mass between regions of the solar-terrestrial system. Solar EUV irradiance modeling will continue to be an important element of that study.

A potential future aerospace requirement will dictate daily or hourly full-disk mod-

eled or predicted irradiance values for satellite operational purposes. Combined with the anticipated availability of hourly spectral and spatial image data, this will challenge our modeling capabilities and will drive operational solar EUV model development.

6. SUMMARY

Empirical solar EUV modeling has progressed since the early 1900s from function-fitting, through fudge factors, to flux measurements, arriving at line-fitting of multiple datasets with linear correlations. Analytic expressions for the solar blackbody spectrum were later offset by empirical increases to match calculated aeronomical parameters. After a series of rocket and satellite measurements which provided typical or reference fluxes, the empirical SERF1, two-component, and SERF2 models were completed between the beginning and end of the 1980s. These provided daily full-disk flux values from 20 to 1050 Å.

New efforts to refine previous EUV models are in progress and will lead to the development of a COSPAR International Reference Solar EUV irradiance model by the SOL-ERS22 program in the mid-1990s. These new models will help advance our understanding of the fundamental coupling of energetics in the Sun-Earth system and will provide the basis for a new generation of operational models by the end of the 1990s.

7. ACKNOWLEDGEMENTS

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