Pergamon

0273–1177(95)00827–6

Adv. Space Res. Vol. 18, No. 3, pp. (3)3–(3)10, 1996

0273–1177/96 $9.50 + 0.00

CURRENT STATUS OF SOLAR EUV MEASUREMENTS AND MODELING

W. K. Tobiska

TELOS/NYMA/JPL, MS 264-765, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A.

ABSTRACT

EUV measurements, modeling, and prediction are a part of the body of information needed for detailing our grasp of what anthropogenic changes are now occurring to the upper atmosphere and ionosphere. Since the next set of full spectrum EUV measurements will likely not occur until the late 1990's, several empirical solar EUV models will help bridge the data gap. These models provide solar EUV flux estimates beyond the low, moderate, or high solar activity levels that are given by reference spectra. Each of the models provides important advantages for certain types of calculations and each model contains inherent weaknesses. An overview is presented of 3 of the primary reference spectra and the 5 principal models in use. Model reliability issues, a graphical comparison between models and rocket data, a description of the proxies used by each model, and examples of studies where EUV model fluxes are compared with ionospheric data are discussed.

INTRODUCTION

Full-disk solar extreme ultraviolet (EUV) irradiances between 1 and 121.6 nm are the fundamental energy input for the terrestrial thermosphere. They are also the primary photoionization source creating the ionosphere. Investigations of the upper atmosphere use modeled photoabsorption and energy transfer processes that require the input of these irradiances. As a result, the daily, accurate, precise, and well-calibrated full-disk irradiances in the EUV solar spectrum are a fundamental parameter for upper atmosphere and ionosphere studies. When irradiance measurements are unavailable, empirical irradiance models, based on ground- and space-based proxies, are used.

Though the term "extreme ultraviolet" is imprecisely defined, this part of the spectrum includes emission lines, continua, bands, and blackbody irradiances. All irradiances less than 200 nm have been historically categorized as the "vacuum ultraviolet" (VUV) while "far ultraviolet" (FUV) has usually been applied to irradiances from 115 to 200 nm. The emission lines and continua which dominate the spectrum between 20 and 115 nm have usually been referred to as the EUV while "X-ray ultraviolet" (XUV) or "soft X-rays" is a term applied to irradiances less than 30 nm dominated by emission lines. These irradiance ranges can generally be mapped from a particular source layer in the solar atmosphere to a particular level of unit optical depth in the terrestrial atmosphere.

Given this solar-terrestrial connection, the motivations for improving solar EUV measurements and modeling come from an effort to understand global climate change and other issues. For example, are there now significant anthropogenic changes occurring in the upper atmosphere as a result of CO_2 and CH_4 convectively mixing from below? Natural, solar-induced perturbations to the upper atmosphere must be quantified to determine human-induced changes. Also, how accurately can "space weather" or "space climatology" be modeled or predicted? This depends, in part, upon the ability to regularly and accurately measure, model, or predict selected solar irradiances, or their proxies, which represent the bulk of solar energy coming into the upper atmosphere. Finally, financial and safety decisions for low-Earth-orbiting spacecraft, based on lifetime (atmospheric drag) and aerobraking predictions, are and will be made using these measured, modeled, and predicted solar EUV irradiances.

DISCUSSION

Full-disk EUV irradiance observations began following the first solar UV rocket in 1946. The early EUV rocket measurements provided estimates of absolute fluxes during specific solar conditions and have been reviewed by Tousey /1/, Timothy /2/, Schmidtke /3/, Lean /4,5/, Rottman /6/, and Tobiska /7/.

Satellite observations of EUV irradiances began intermittently in 1962 and provided insights into wavelength-dependent daily, solar-rotational, active region evolution, and solar cycle variations. Schmidtke /8/ provided an overview of these observations and an adaptation of his work is shown in Figure 1.

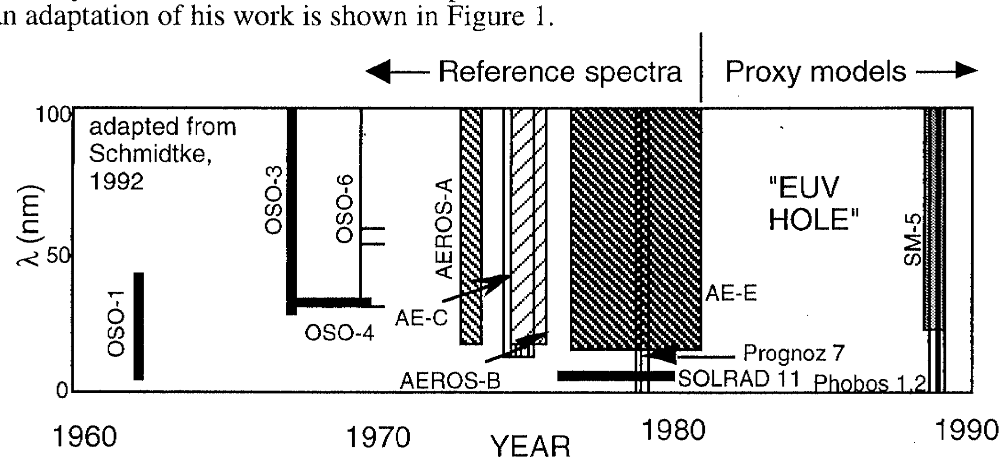

Fig. 1. Adapted from Schmidtke /8/, the solar EUV has been intermittently measured by satellites since the 1960's across different parts of the spectrum.

Several important features in this figure demonstrate the current status of EUV measurements and modeling. First, the longest consistent set of measurements throughout most of the spectrum were those by the Atmosphere Explorer E (AE-E) satellite (from mid-1977 to the end of 1980). Since the end of AE-E, only occasional rocket flights interrupted the "EUV hole" (Donnelly /9/). The next full-spectrum daily measurements will not occur until the late 1990's, i.e., nearly twenty years after AE-E. An important consequence of the AE-E measurements was the creation of proxy models for estimating daily EUV fluxes. These models followed a period prior to the end of AE-E that was devoted to the development of reference spectra.

There have been several reference spectra compiled for varying solar conditions. Among these are the Donnelly and Pope /10/, F74113 /11/, SC21REFW /12/, F79050N /13/, and the ASSI /14/ spectra. The primary objective in the creation of reference spectra has been to provide the aeronomical community with an estimate of solar irradiances for low, moderate, and high solar activity. Figure 2 graphically compares the Donnelly and Pope (D&P) moderate solar activity, the SC21REFW low activity, and the ASSI moderate activity spectra.

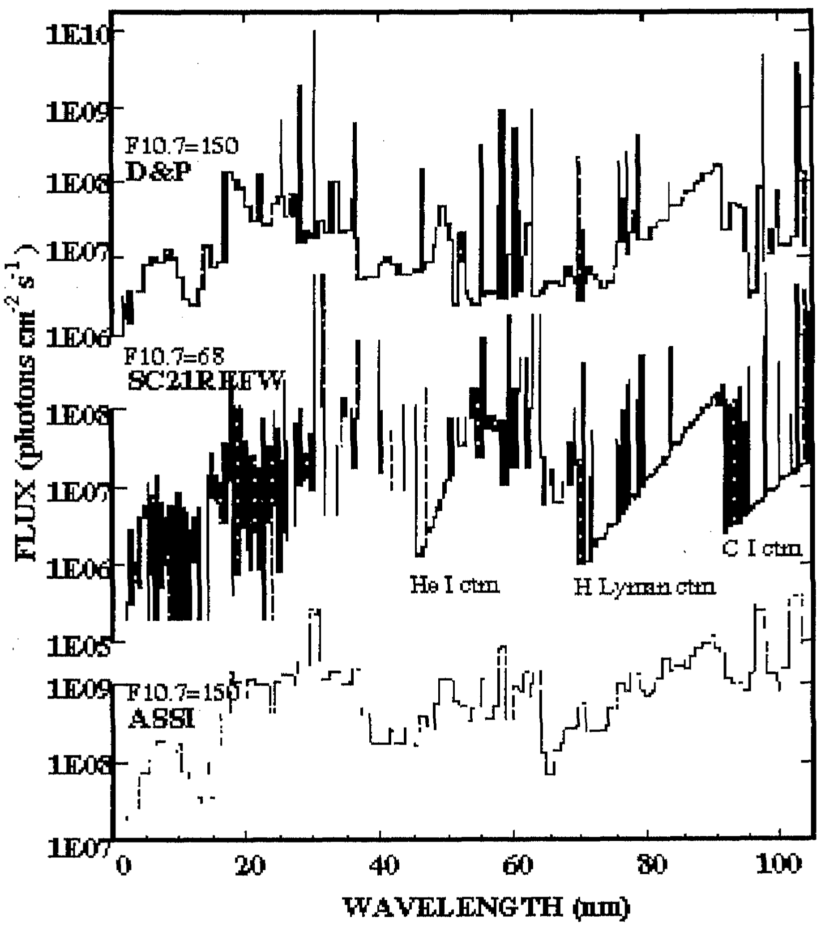

Fig. 2. Three reference spectra for low and moderate solar activity where the 10.7 cm radio flux (F10.7) is 68 and 150, respectively. General differences between spectra result from varying flux magnitudes during low and moderate solar activity and from different wavelength binning templates used in each spectrum.

In all three examples, each of which are composite spectra of satellite and rocket measurements, the highest photon flux emission lines rise prominently above the He I, H Lyman, and C I continua emissions longward of 40 nm. Shortward of these continua, individual emission lines rise above the insignificant solar blackbody emission. Each spectrum has been published in tabulated form and each uses a different wavelength binning interval which explains some of the graphical differences. Finally, the flux magnitudes from either low or moderate solar activity create differences between the SC21REFW and D&P/ASSI spectra, respectively.

Solar EUV empirical proxy models were developed when sufficiently long data sets became available. This condition was first satisfied by the measurements from AE-E. In some respect, these models represented an advance over the solar activity reference spectra. Researchers now had the tools to estimate daily, full-disk, multi-spectral EUV irradiances at 1 AU. However, there are limitations as well. Most of the models are derived from intermediate-term data sets obtained more than a decade ago at the rise and height of solar cycle 21. Models will still benefit from data sets to be obtained during solar cycle decline and minimum conditions. There are likewise questions about the reliability of some EUV proxies during highor low solar activity (AE-E Lyman-α and F10.7, respectively) . Finally, some models' fluxes differ from the data used in their derivations (SERF1 and SERF2), some are based upon only one intermediate-term data set (SERF1 and NUSINOV), and some do not have consistent flux magnitudes between adjacent XUV wavelength bins (EUV94X shortward of 15 nm). It is not surprising that work continues toward achieving empirical models that are aeronomically reliable.

A comparative technique has been used by Ogawa et al. /15/ to graphically show the similarities and differences between measured and modeled fluxes from 5 to 57.5 nm. This range contains a mix of coronal and chromospheric emission lines as well as continua. Figure 3, adapted from Ogawa et al. /15/, shows F10.7 versus the total integrated flux of this wavelength interval.

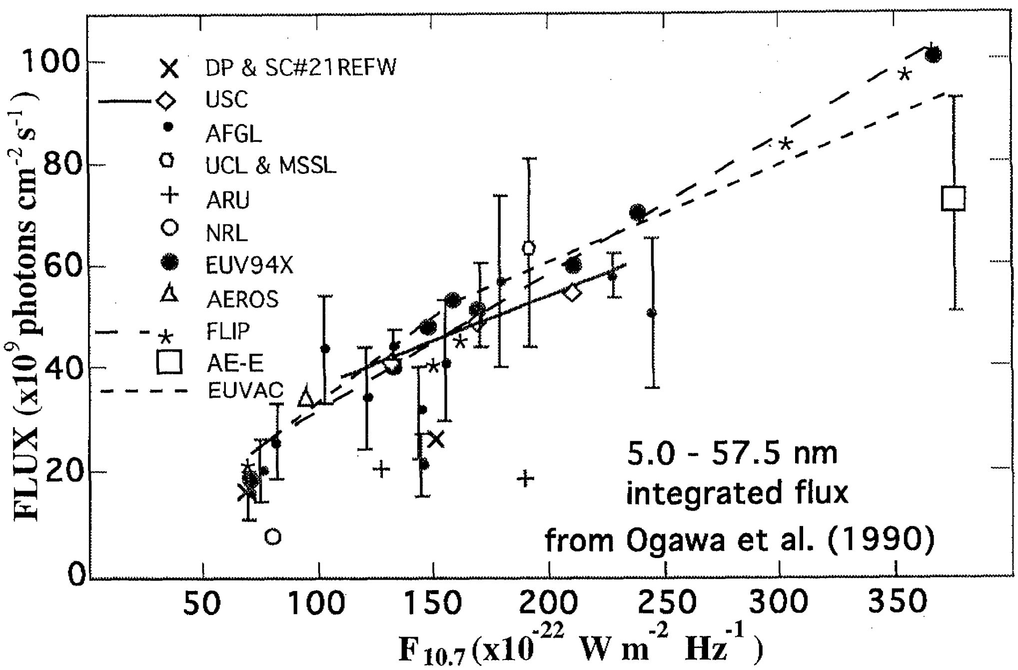

Fig. 3. Measured and modeled solar EUV flux from 5 to 57.5 nm for varying levels of F10.7. Institutions in the legend are described by Ogawa et al. /15/ while models are described by Tobiska /7,17/ and Richards et al. /21/.

Some features are immediately apparent in Figure 3. First, nearly all measurements and models show increasing flux for increasing levels of solar activity represented by F10.7. However, the trend is non-linear between solar minimum and maximum. The integrated EUV flux falls off at a different rate than F10.7 indicating a possible "threshold" effect for F10.7 at low activity or a "saturation" effect at high activity. Second, for low to moderate levels of solar activity, the EUV94X and EUVAC models fit within the error bars of the measurements. However, both models using F10.7 diverge during high solar activity from what might be expected. Both issues raise the question of the suitability of F10.7 as an indicator for EUV wavelengths shown here.

Table 1 lists the most prominent empirical models and their proxies. SERF1 /12/, SERF2 /16/, EUV91 /17/, EUV94X /18/, and SERF3 (R.F. Donnelly, private communication, 1991) all rely on both ground- and space-based proxies while the Nusinov /19,20/ and EUVAC /21/ models utilize the ground-based F10.7 proxy. The proxy emission themselves come from different solar atmosphere source regions which explains why their time variations generally represent EUV emissions coming from similar regions. For example, hot corona proxies are the 335 FeXVI and the 1-8 Å X-ray emissions. F10.7 and its 81-day running average value (F81) are dominated by coronal and transition region processes. H Lyman-β, H Lyman-α, HeI 10,830 Å equivalent width, MgII core-to-wing ratio, and CaK 1 Å emissions/indices are all dominated by chromospheric region processes.

TABLE 1. Proxies for empirical EUV models

Model / Proxy	SERF1	Nusinov	SERF2/ EUV91/94X	SERF3	EUVAC
335 FeXVI	X[1]				
1026 Lyβ	X[1]				
F81	X[2]	X[3]	X	X[5]	X
F10.7	X[2]	X	X	X[5]	X
1216 Lyα			X[4]	X[5]	
HeI 10,830			X[4]	X[5]	
MgII c/w				X[5]	
1-8 Å				X[5]	
Ca K 1 Å				X[5]	

Space-based proxy (shaded)
Ground-based proxy (clear)
[1]Used in the "class" model during the AE-E time period.
[2]Used in the "association" model outside the AE-E time period.
[3]F_b is an empirically-determined, long-term active region background component.
[4]These two proxies may be substituted for each other or may be approximated by F10.7 from linear correlation coefficients.
[5]The model is not yet published although correlations between some proxies and wavelengths have been made (Donnelly, private communication, 1993).

In addition to direct flux measurement–model comparisons, an important check on empirical models are the results obtained from aeronomical model calculations using modeled EUV fluxes. Recent work by Buonsanto et al. /22/ compares Millstone Hill E-F_1 measured electron densities with modeled densities derived from several sources of solar EUV flux. Balan et al. /23/ compare ionospheric electron content from several stations with modeled solar fluxes. In general, these studies show improvements in modeled versus measured data sets, although unresolved differences still exist.

These studies have helped pose several contemporary questions. For example, during solar minimum, were early rocket-measured fluxes between 5 and 57.5 nm too low? Should those fluxes be increased by up to a factor of 2? Why are the measured 1 to 10 nm soft X-ray fluxes for all levels of solar activity lower than what is expected from modeled and measured thermospheric nitric oxide? What are reasonable levels of H Lyman-β based on the measured E-F_1 peak-to-valley electron densities? Finally, are there more useful wavelength binning templates for the EUV than those presently being used?

For significant improvements in empirical modeling, the measurement of daily, accurate, precise, and well-calibrated EUV irradiances is the first priority. However, funding for instrumentation, opportunities for flight, and methods of calibration are continuing concerns. With increased near-Earth space activity, there will be an interest in predicting the solar EUV irradiances for the next day, week, 27-days, six months, and solar cycle.

An example of the current state of predictive capability (EUV94X) is shown in Figure 4. Modeled H Lyman-β flux is shown in the first nine months of 1993 while the predicted flux, based on predicted F10.7 flux, is shown into the next solar cycle.

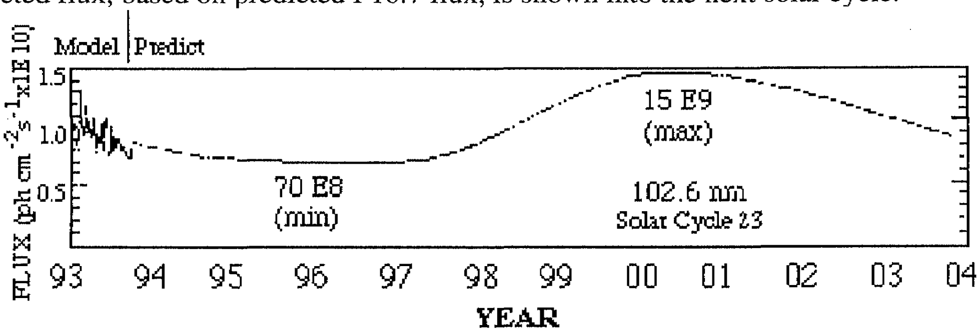

Fig. 4. Modeled and predicted H Lyman-β flux from the EUV94X model. Solar cycle 22 average minimum flux for this emission is predicted as 0.7×10^{10} photons $cm^{-2}\ s^{-1}$ during 1996 while cycle 23 average maximum is predicted to double to 1.5×10^{10} photons $cm^{-2}\ s^{-1}$ during the year 2000.

SUMMARY

There is continuing work to improve the regularity, accuracy, precision, and calibration of daily-measured solar EUV irradiances at 1 AU. Although there were many intermittent or partial spectrum solar EUV measurements made by satellites from the 1960's into the 1980's, the next set of full spectrum measurements will not occur until the late 1990's. This will be nearly two decades after the AE-E measurements.

In order to fill this years-long data gap and to provide a reliable tool for aeronomical calculations which uses solar EUV as an energy input for the upper atmosphere, several empirical solar EUV models have been developed. These provide solar EUV flux estimates beyond the general levels of low, moderate, or high solar activity exemplified by reference spectra. Each of the models has advantages for certain types of calculations and each contains inherent weaknesses. An overview of 3 of the primary reference spectra and 5 empirical models is presented. Comparison of models and rocket data, a listing of the proxies used by each model, and model reliability issues are discussed. Improved models can help answer contemporary upper atmosphere and ionosphere questions and can contribute to resolving bigger questions such as "what are the anthropogenic changes now occurring to the upper atmosphere and ionosphere?"

ACKNOWLEDGMENTS

The author appreciates the support given by the Telos Information Systems and by NYMA for this work.

REFERENCES

1. Tousey, R., Solar spectroscopy in the far ultraviolet, *J. Opt. Soc. Am.*, **51**, 384-395 (1961).

2. Timothy, J.G., The solar spectrum between 300 and 1200 Å, in *The Solar Output and its Variation*, ed. O.R. White, pp. 133-150, Colorado University Associated Press, Boulder, Colo. (1977).

3. Schmidtke, G., Modelling of the solar extreme ultraviolet irradiance for aeronomic applications, in *Handbuch der Physik*, Vol. XLIX/7, Geophysics III, Part VII, ed. S. Flugge, pp. 1-55, Springer-Verlag, Berlin (1984).

4. Lean, J.L., Solar ultraviolet irradiance variations: a review, *J. Geophys. Res.*, **92**, 839-868 (1987).

5. Lean, J., Variations in the Sun's radiative output, *Rev. Geophys. Space Phys.*, **29**, 505-535 (1991).

6. Rottman, G.J., Observations of solar UV and EUV variability, *Adv. Space Res.*, **8**, 53-66 (1988).

7. Tobiska, W.K., Recent solar extreme ultraviolet irradiance observations and modeling: a review, *J. Geophys. Res.*, **98**, 18879-18893 (1993).

8. Schmidtke, G., Observations of the solar EUV spectral irradiance, in *Proceedings of the Workshop on the Solar Electromagnetic Radiation Flux Study for Solar Cycle 22*, ed. R.F. Donnelly, pp. 303-318, Space Environment Laboratory, National Oceanic and Atmospheric Administration, Boulder, Colo. (1992).

9. Donnelly, R.F., Gaps between solar UV and EUV radiometry and atmospheric sciences, in *Solar Radiative Output Variation*, ed. P. Foukal, pp. 139-142, Cambridge Research and Instrumentation, Cambridge, Mass. (1987).

10. Donnelly, R.F. and J.H. Pope, The 1-3000 Å solar flux for a moderate level of solar activity for use in modeling the ionosphere and upper atmosphere, *Tech. Rep. ERL 276-SEL 25*, National Oceanic and Atmospheric Administration, Boulder, Colo. (1973).

11. Heroux, L. and H.E. Hinteregger, Aeronomical reference spectrum for solar UV below 2000 Å, *J. Geophys. Res.*, **83**, 5305-5308 (1978).

12. Hinteregger, H.E., K. Fukui, and B.R. Gilson, Observational, reference and model data on solar EUV, from measurements on AE-E, *Geophys. Res. Lett.*, **8**, 1147-1150 (1981).

13. Hinteregger, H.E., private communication to SERFS/WITS (1985).

14. Schmidtke, G., T.N. Woods, J. Worden, G.J. Rottman, H. Doll, C. Wita, and S.C. Solomon, Solar EUV irradiance from the San Marco ASSI: a reference spectrum, *Geophys. Res. Lett.*, **19**, 2175-2178 (1992).

15. Ogawa, H.S., L.R. Canfield, D. McMullin, and D.L. Judge, Sounding rocket measurement of absolute solar EUV flux utilizing a silicon photodiode, *J. Geophys. Res.*, **95**, 4291-4295 (1990).

16. Tobiska, W.K. and C.A. Barth, A solar EUV flux model, *J. Geophys. Res.*, **95**, 8243-8251 (1990).

17. Tobiska, W.K., Revised solar extreme ultraviolet flux model, *J. Atmos. Terr. Phys.*, **53**, 1005-1018 (1991).

18. Tobiska, W.K., Modeled soft X-ray solar irradiances, *Solar Phys.*, **152**, 207-215 (1994).

19. Bruevich, E.A. and Nusinov, A.A., Spectrum of short-wavelength radiation for aeronomic calculations at various solar activity levels, *Geomagn. Aeron.*, **24**, 478-481 (1984).

20. Nusinov, A.A., Models for prediction of EUV- and X-ray solar radiation based on 10.7-cm radio emission, in *Proceedings of the Workshop on the Solar Electromagnetic Radiation Flux Study for Solar Cycle* 22, ed. R.F. Donnelly, pp. 354-359, Space Environment Laboratory, National Oceanic and Atmospheric Administration, Boulder, Colo. (1992).

21. Richards, P.G., J.A. Fennelly, and D.G. Torr, EUVAC: A solar EUV flux model for aeronomic calculations, *J. Geophys. Res.*, **99**, 8981-8992 (1994).

22. Buonsanto, M.J., S.C. Solomon, and W.K. Tobiska, Comparison of measured and modeled solar EUV flux and its effect on the E-F1 region ionosphere, *J. Geophys. Res.*, **97**, 10513-10524 (1992).

23. Balan, N., G.J. Bailey, and B. Jayachandran, Ionospheric evidence for a nonlinear relationship between the solar e.u.v. and 10.7 cm fluxes during an intense solar cycle, *Planet. Space Sci.*, **41**(2), 141-145 (1993).