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Measurement and Modeling of Solar EUV/UV Radiation

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1 Introduction

An important element of the TIGER program is to understand solar-terrestrial relations, including climatology and space weather. This activity starts with knowledge of the Sun and its connection to the Earth. This first section of the proceedings contains a collection of papers that describe current international activity to measure and model the solar ultraviolet (UV), far ultraviolet (FUV), extreme ultraviolet (EUV), and soft X-ray (XUV) irradiances (collectively called EUV/UV here). The instrumentation being developed for future measurements is described in Section 2, "EUV/UV Space Instrumentation."

The energy from solar core nuclear fusion is transported to the solar visible surface over millions of years by interior radiative and convective processes. Beyond the solar photosphere, thermal and magnetic processes carry a highly ionized plasma into the chromosphere and corona. This plasma produces radiation throughout the electromagnetic spectrum. Temporal irradiance variations are a strong function of wavelength in the UV, FUV, EUV, and XUV solar irradiances and are a fundamental forcing mechanism to the terrestrial middle and upper atmospheres. Through its terrestrial interactions, this radiation helps create short-term space weather as well as the long-term global climate. Section 4 of these proceedings, "Modeling of the Thermosphere/Ionosphere and Measurement of Relevant Thermospheric-Ionospheric Parameters from Space," includes several papers that detail these interactions.

The accurate characterization of solar irradiances extending from the soft X-rays through the UV wavelengths, e.g., 1-400 nm, is important for answering key scientific questions that have been posed to our community. For example,

1. *Do we know the primary mechanisms by which solar UV, FUV, EUV, and XUV irradiance variations affect terrestrial global climate change and/or weather? If so, what is their significance and can we predict those variations?*
2. *Do we know the primary mechanisms by which solar EUV/UV irradiance variations affect middle and upper atmosphere chemically-active minor species and have we determined the relative importance of solar versus auroral energy inputs?*
3. *How does solar forcing compare with forcing from other sources such as increasing concentrations of radiatively-active gases and atmospheric aerosols?*
4. *How sensitive is the Earth's climate to solar radiation changes and what time scales of solar variability are significant to climate?*
5. *How might solar variability affect global warming projections?*
6. *Are there signatures of solar influences distinct from anthropogenic effects?*
7. *What are the implications for humanity from solar influences to the terrestrial climate?*

The role solar irradiance variations play in such a climate change is still unknown but solar-induced changes could significantly impact these variations in either direction of temperature change. The current level of known solar cycle variability simply modulates the net anthropogenic increase in climate forcing and solar XUV-UV irradiances contribute an important part of the middle and upper atmosphere energy balance.

The papers of this section describe the advances being made in solar XUV-UV irradiance measurements and modeling. These advances will likely contribute some answers to these larger scientific questions in the coming years.

2 Measurements

Following the first solar UV rocket in 1946, EUV rocket observations were made and provided absolute flux measurements. Reviews by Tousey [1961], Timothy [1977], Schmidtke [1984], Lean [1987, 1991], Rottman [1988], and Tobiska [1993] detail the early history.

EUV satellite observations exist since 1962. These provide insights into wavelength-dependent daily, solar rotational, active region evolution, and solar cycle variations. Satellites include OSO 1 (1962), OSO 3 (1967), OSO 4 (1967-69), OSO 6 (1969), AEROS A (1972), AE-C (1974-75), AEROS B (1974-75), AE-E (1977-80), SOLRAD 11 (1977-79), PROGNOZ 7-10 (1978-85), San

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Marco 5 (1988), PHOBOS 1&2 (1988-89), YOHKOH (1991-), CORONAS-I (1994), INTERBALL-1 (1995-96), ELECTRO (1995-98), and SOHO (1995-). Future XUV-EUV measurements are planned on the TIMED (2001-), ISS (2003-), GOES (2004-), and Solar Patrol (2004-) missions.

Sounding rockets have made spectral, image, and integrated bandpass observations throughout the EUV, especially during the "EUV hole" where few measurements were made in the 1980's. They include USC (1982, 1983, 1988, 1996), LASP (1988, 1989, 1992, 1993, 1994, 1996, 1998), and GSFC (1989).

Solar UV satellite observations have been made by AEROS A (1972), AE-C (1974-75), AEROS B (1974-75), KOSMOS-381 (1974), AE-E (1977-1980), Nimbus 7 (1978-1987), SME (1981-1989), NOAA 9,11 (1985-), ATLAS 1,2 (1992,1993), UARS (1991-), and GOME (1995-). The NOAA 14 (2000-), TIMED (2001-), EOS/TSIM (2002-), and ISS (2003-) missions will provide future measurements in the UV spectral range. Descriptions of several new instruments and their observation objectives from the XUV-UV are described in these symposium papers.

Reference spectra have been particularly useful for characterizing the highly variable XUV-EUV spectral range. Prior to AE-E, reference XUV-EUV spectra were developed from rocket observation. Several spectra have been widely used. For example, the Donnelly and Pope [1973] moderate solar activity (F10.7 = 150) reference spectrum was a composite of several rocket observations with a wavelength bin size of 0.3 to 1 nm. Several discrete, important lines are included and this was the first reference solar spectrum in the EUV.

Hinteregger *et al.* [1981] provided a reference spectrum for low solar activity (F10.7 = 68) from a composite of rocket and satellite observations with a wavelength bin size of 0.1 to 0.2 nm. All discrete, important lines are included in this reference spectrum (SC#21REFW). AFGL reference spectrum (F79226) for high solar activity and (F79050N) for anomalously high solar activity have also been used in the literature [Hinteregger, private communication, 1985].

Schmidtke *et al.* [1992] have provided a moderate solar activity (F10.7 = 150) composite of rocket (LASP) and satellite (ASSI) observations with a wavelength bin size of 1.0 nm. All discrete, important lines are included within each bin.

The ASTM E490 composite reference spectrum and standard is based on several data sets. UARS/ATLAS-2 moderate solar activity spectra are used between 119.5 and 379.5 nm which are averages of the SUSIM and SOLSTICE measurements [Woods *et al.*, 1996]. These data were scaled by 0.96843 to match the Neckel and Labs [1984] data between 330 and 410 nm. Thuillier [1998a,b] provided a spectrum that is used above 379.7 nm.

3 Modeling

Beyond reference spectra, and post AE-E, the "EUV hole" has forced the development of empirical solar EUV models to fill the temporal and spectral gaps. All empirical solar EUV irradiance models, i.e., SERF1, Nusinov, SERF2, EUV91, SERF3, EUVAC, EUV97, and SOLAR2000 derive at the minimum from AE-E data. There has only been one rigorous comparison made between EUV models [Lean, 1990] where SERF1 and SERF2 were compared with the data used to derive those models. Comparisons have been made using coupled solar – ionospheric models with ionospheric electron content or densities and these comparisons have pointed to areas requiring model improvement. A short description of the EUV empirical models outlines the state of empirical modeling, with the exception of SERF3 which has not yet been published [Donnelly, private communication, 1998].

SERF1. Hinteregger [Hinteregger, *et al.*, 1981; private communication, 1985] provided a model where Lyman-β is used as a proxy for chromospheric emissions during the AE-E timeframe. Fe XVI is used as a proxy for coronal emissions. Outside of AE-E, F10.7 is used as the sole proxy.

Nusinov. Nusinov [1984] developed a model with an empirically-determined active region background component, Fb, which incorporated modeled physical features. It is combined with daily F10.7 to produce full-disk irradiances.

EUVAC. Richards *et al.* [1994a,b] describe a solar EUV flux model which reproduces the integrated EUV flux and the shape of the measured photoelectron flux spectrum in 37 wavelength bins. It is based on the measured F74113 solar EUV reference spectrum and the solar cycle variation of the flux observed by the AE-E satellite.

EUV97. Tobiska and Eparvier [1998] upgraded a model for aeronomical and space environment uses with heritage from SERF2 [Tobiska and Barth, 1990] and EUV91 [Tobiska, 1991]. Lyman-α is used as the chromospheric proxy and F10.7 is used as the coronal proxy. EUV97 models daily irradiances from 1947 to the end of solar cycle 23 in 39 wavelength lines or bins.

SOLAR2000. Tobiska *et al.* [2000] and Tobiska (this proceedings) describe an empirical model of the full solar spectrum. This model incorporates both proxy model and reference spectra to produce a fully self-consistent spectrum with 1 nm resolution from the X-rays to radio wavelengths. It also provides an operational capability, the E10.7 proxy of the EUV, a forecast capability, and will be compliant with the developing ISO solar standard.

UV and FUV models. Three solar UV models have been developed which represent the spectral range of 120-200 nm, i.e., fluxes that originate in the solar photosphere and chromosphere. Cook *et al.* [1980] developed a two-component model that used a parameterization of the daily sunspot number to provide plage region and quiet region emission. Lean *et al.* [1982] improved upon the long-term absolute irradiance variation with a three-component model that incorporates flux contributions from the quiet sun, moderately bright active network, and bright plage areas. Worden [1996] used improved UARS/SOLSTICE FUV irradiances to develop a similar three-component model as well as an empirical model based on a Lyman-α plage index proxy.

Semi-empirical and first principles models. There is a significant community that is developing semi-empirical and first principles models of the Sun's radiative output. These proceedings and this section do not include papers from their work. However, groups at HAO, CFA, NRL, and Zurich have actively organized this field. Example of their work include Fontenla, *et al.* [1999], Fox, *et al.* [2000], Kurucz [1998], Warren, *et al.* [1998a, 1998b], Solanki, *et al.* [1998], and Fligge, *et al.* [2000]. Readers are directed toward their work and others that can also be found in recent proceedings of the ISSI Bern 1999 meeting (ed. von Steiger) and the IUGG Birmingham 1999 meeting (eds. Pap and Fröhlich).

4 Section overview

There are eighteen papers in this section describing XUV-UV measurements and modeling. Past, present, and future measurement discussions are covered in eight papers:

1. "The Absolute Solar Spectral Irradiance from 200 to 2500 nm as Measured by the SOLSPEC Spectrometer with the ATLAS and EURECA Missions" (G. Thuillier, M. Hersé, P.C. Simon, D. Labs, H. Mandel, D. Gillotay, W. Petermans) reports on the spectral measurements by the SOLSPEC instrument during flights in the 1990's;
2. "Solar Irradiances of Ultraviolet Emission Lines Measured during the Minimum of Sunspot Activity in 1996 and 1997" (K. Wilhelm, P. Lemaire, I.E. Dammasch, J. Hollandt, U. Schuehle, W. Curdt, T. Kucera, D.M. Hassler, and M.C.E. Huber) describes the calibrated SUMER measurements of EUV emission lines;
3. "TIMED Solar EUV Experiment" (T.N. Woods, S. Bailey, F. Eparvier, G. Lawrence, J. Lean, B. McClintock, R. Roble, G.J. Rottman, S.C. Solomon, W.K. Tobiska, O.R. White) describes the instrumentation and measurement objectives of the SEE experiment on the TIMED mission;
4. "Solar Extreme Ultraviolet Irradiance Measurements from Sounding Rockets during Solar Cycle 22" (T.N. Woods, G.J. Rottman, S.C. Solomon) compares sounding rocket measurements during the 1990's with the AE-E measurements;
5. "Solar UV Irradiance Measurements: the UARS and EOS SOLSTICE" (G. Rottman) reports on the UARS UV measurements since 1991 and the upcoming EOS UV measurement objectives;
6. "Soft X-Rays in the 00:18 UT Solar Flare on April 22, 1994" (G.E. Kocharov, Yu.E. Charikov, V.P. Lazutkov, G.A. Matveev, Yu.N. Nitsora, M.I. Savchenko, and D.V. Skorodumov) reports on the measurements by the IRIS instrument of solar soft X-ray flares;
7. "The SOHO CELIAS/SEM Data Base" (D.L. Judge, H.S. Ogawa, D.R. McMullin, and P. Gangopadhyay) reports on the calibrated SEM measurements since solar minimum in 1996; and
8. "Radiance Variations of Vacuum-ultraviolet Emission Lines of the Quiet Sun Observed with SUMER on SOHO" (U. Schühle, A. Pauluhn, J. Hollandt, P. Lemaire, and K. Wilhelm) describe the characteristics of several important solar lines and their variations since 1996.

Solar irradiance analysis, modeling, and proxy development are described in nine papers:

1. "Solar EUV Observations and Proxies: Analysis of the Errors and Presentation of a Solution" (R. Viereck) details the development of solar proxies;
2. "Status of the SOLAR2000 Solar Irradiance Model" (W.K. Tobiska) outlines the development of the SOLAR2000 empirical model and its characteristics;
3. "X-ray Precursors in Solar Flares" (Yu.E. Charikov) describes the stages of a flare with relevance toward predictions;
4. "Connections between X, EUV/UV and VIS solar activity" (R. Hammer, H. Schleicher) uses first principles modeling to describe the connections between various emissions and their sources;
5. "EUV Measurements and Solar Active Region Models" (J. Hildebrandt) compares modeled solar irradiances with satellite measurements;
6. "An Analysis of the Time Series from the First Order Channel of the SOHO CELIAS SEM Experiment" (L.E. Floyd and L.C. Herring) uses a regression technique to determine the morphology of the SEM 30.4 nm line;
7. "Variations in the H Lyα-Intensity in Solar Activity Cycles from Measurements onboard Satellites and Rockets" (T.V. Kazachevskaya and V.V. Katyushina) describes the minimum, maximum values and differences between several Lyman-α measurements over several cycles;
8. "Modern Understanding of the Solar Activity Cycle as a Global Process from Optical and Radio Observations" (G.B. Gelfreikh, V.I. Makarov, and A.G. Tlatov) describes radio wavelength observations and their use as proxies; and
9. "Solar EUV Quasi-biannual Variations" (G.S. Ivanov-Kholodny) reports on a method of using ionospheric measurements to derive solar EUV flux for long-term studies.

One paper describes the development of a solar irradiance standard: "Status of the Draft ISO Solar Irradiance Standard" (W.K. Tobiska and A.A. Nusinov) presents the details of the International Standards Organization efforts to develop a solar irradiance standard.

5 Summary

These papers, having been presented during two TIGER symposia in 1998 and 1999, represent the state-of-the-art solar XUV-UV irradiance measurement and modeling activities during the next decade. We thank each author for his or her contribution to these proceedings and wish success for each new step in our collective attempt to understand the Sun's influence on our terrestrial environment.

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