MODELED SOFT X-RAY SOLAR IRRADIANCES

W. KENT TOBISKA

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

Abstract. Solar soft X-rays have historically been inaccurately modeled in both relative variations and absolute magnitudes by empirical solar extreme ultraviolet (EUV) irradiance models. This is a result of the use of a limited number of rocket data sets which were primarily associated with the calibration of the AE-E satellite EUV data set. In this work, the EUV91 solar EUV irradiance model has been upgraded to improve the accuracy of the 3.0 to 5.0 nm relative irradiance variations. The absolute magnitude estimate of the flux in this wavelength range has also been revised upwards. The upgrade was accomplished by first digitizing the SOLRAD 11 satellite 4.4 to 6.0 nm measured energy flux data set, then extracting and extrapolating a derived 3.0 to 5.0 nm photon flux from these data, and finally by performing a correlation between these derived data and the daily and 81-day mean 10.7 cm radio flux emission using a multiple linear regression technique. A correlation coefficient of greater than 0.9 was obtained between the dependent and independent data sets. The derived and modeled 3.0 to 5.0 nm flux varies by more than an order of magnitude over a solar cycle, ranging from a flux below 1×10^8 to a flux greater than 1×10^9 photons cm^{-2} s^{-1}. Solar rotational (27-day) variations in the flux magnitude are a factor of 2. The derived and modeled irradiance absolute values are an order of magnitude greater than previous values from rocket data sets related to the calibration of the AE-E satellite.

1. Introduction

Extreme ultraviolet (EUV) empirical models are important from an aeronomical perspective. The solar EUV irradiance is a fundamental thermospheric and ionospheric energy input though there are few measured data. The satellite data sets that exist extend through various levels of solar activity though they often contain missing days and large uncertainties. Rocket measurements have greater accuracy compared to the satellite data yet only provide measurements for very short time intervals. Given these conditions, models are important.

Some unresolved solar EUV and soft X-ray questions are posed. For example, during solar cycle minimum conditions is an EUV/soft X-ray value for the 5 to 57.5 nm total integrated flux interval higher than irradiances measured by rockets in the 1970s? Richards and Torr (1984), Ogawa and Judge (1986), Link *et al.* (1988), and Winningham *et al.* (1989) suggest that some or all of the total flux in that wavelength range is higher during low solar activity by up to a factor of 2. This implies that either the entire range of 5 to 57.5 nm has greater flux or that the shorter wavelengths have dramatically more flux and the longer wavelengths have little increased flux compared to those variations presently modeled. In the latter scenario, the total flux of 5 to 57.5 nm is only slightly higher; the longer wavelengths contribute the bulk of the measured photons while the shorter wavelengths provide substantially more secondary ionization energy into the lower thermosphere and E-region ionosphere.

Solar Physics **152**: 207–215, 1994.

A corollary question is whether or not a value for the soft X rays (0.1 to 10 nm) should be used which is substantially higher by more than an order of magnitude at all levels of solar activity? Barth *et al.* (1988) and Siskind *et al.* (1990) suggest from lower thermospheric nitric oxide data and model comparisons that these soft X rays should be scaled upwards significantly (up to 60 times).

Additionally, measured E-region electron densities are higher by 30 to 50%, depending upon date, compared to state-of-the-art ionospheric model calculations (PRIMO workshop, 1991 CEDAR meeting; M. Buonsanto, private communication, 1991). Even slight increases in solar soft X-ray irradiance values on the order of a few percent would improve the modeled electron density values.

In the past, this solar soft X-ray flux has been modeled with data from AFGL rocket data (Hinteregger *et al.*, 1981) which has been extrapolated into a time series based upon measurements by the AE-E satellite. The AE-E instruments themselves did not measure below 15 nm. The low, moderate, and high solar activity measurements in the wavelength range of 4.4–6.0 nm by the SOLRAD 11 (SR11) satellites (Kreplin, 1970; Kreplin *et al.*, 1977; Kahler and Kreplin, 1991; Kreplin and Horan, 1992) provide new material for modelers, especially for relative day-to-day solar variability. Thus, the SR11 data may provide plausible answers to the questions posed above.

2. Derivation of the SOLRAD 11 3.0 – 5.0 nm Data

In order to develop linear regression coefficients between the SR11 4.4–6.0 nm energy flux data and ground-observed proxy data which can be used to model the flux, the SR11 data were processed in several steps. The published data were first digitized and recalibrated so that the digitized data matched the published data. Then the data were transformed from 4.4–6.0 nm energy flux values into derived 3.0–5.0 nm photon flux values. This process enabled the derived SR11 data to be compared with previous rocket measurements related to the AE-E calibration as described by Hinteregger *et al.* (1981) (these data are referred to herein as HEH) and permitted linear regressions to be conducted with proxy data sets.

2.1. DIGITIZATION OF THE SOLRAD 11 44 – 60 Å DATA

The published 4.4–6.0 nm energy flux data of Kreplin and Horan (1992) were photocopied then scanned into a TIFF format digital image that is readable by a MacIntosh computer. The image was manually edited to remove all textual and axes detail while leaving the 4.4–6.0 nm energy flux time series intact. MacDrawPro® software was used to perform these tasks.

The image time series was next converted to a vector of x-y coordinates (uncalibrated in the time and flux value dimensions) using the NIH Image 1.45 software. Figure 1 demonstrates the method by which data were vectorized. The scanned time series is rotated 90° clockwise, ANDed with a mask of lines to create a scatter plot, then analyzed to read out the Y and X values of the points.

The linear x-y values were recalibrated back to the original logarithmic values of the published energy flux time series by the inverse of the relationship

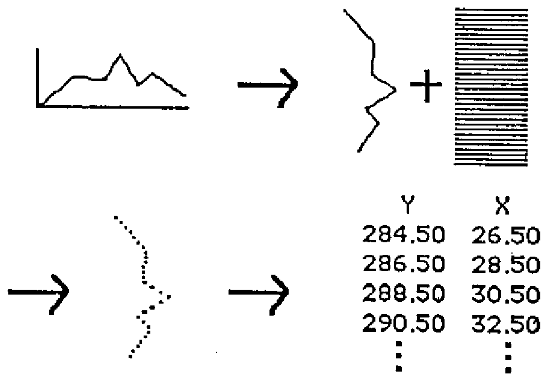

Fig. 1. The scanned TIFF image digital time series is rotated 90° clock-wise, ANDed with a mask of lines to create a scatter plot, then analyzed to read out the linearized Y and X values of the points (NIH Image 1.45 handbook).

$$y = a + b \bullet \mathrm{alog}_{10}\, z \tag{1}$$

where z is the recalibrated, digital, logarithmic energy flux value, y is the linear value from the scanned image, and a and b are the linear offset and slope coefficients from the scanned data. The estimated temporal uncertainty introduced into the data by this digitization method was ±1% and the flux magnitude uncertainty was up to 10%. F.E. Eparvier (private communication, 1993) indicated that his independent digitization of these data yielded values within 5% of the absolute numbers used in this study. Figure 2 (a) shows the digitized SR 4.4–6.0 nm energy flux beginning with SR7A and continuing through SR11.

2.2. TRANSFORMATION: SOLRAD ENERGY FLUX TO PHOTON FLUX

The derived 4.4–6.0 nm photon flux, $F_{44\text{-}60}$, was obtained by converting the calibrated 4.4–6.0 nm energy flux, $E_{44\text{-}60}$, to photon flux by

$$F_{44\text{-}60} = E_{44\text{-}60} \; \frac{\lambda}{12400 \bullet 1.6022 \times 10^{-12}} \tag{2}$$

where λ is 45.5 Å and is the wavelength at which 50% of the flux has entered the photometer bandpass beginning with the filter cutoff at 43 Å (cf. figure 4, Kreplin and Horan, 1992).

The 3.0–5.0 nm photon flux was derived from the 4.4–6.0 nm photon flux by the following algorithms. The photon flux for the combined coronal and chromospheric components is defined as

$$F_{30\text{-}50} = F_{44\text{-}60} \; \frac{A_1}{B_1} \tag{3}$$

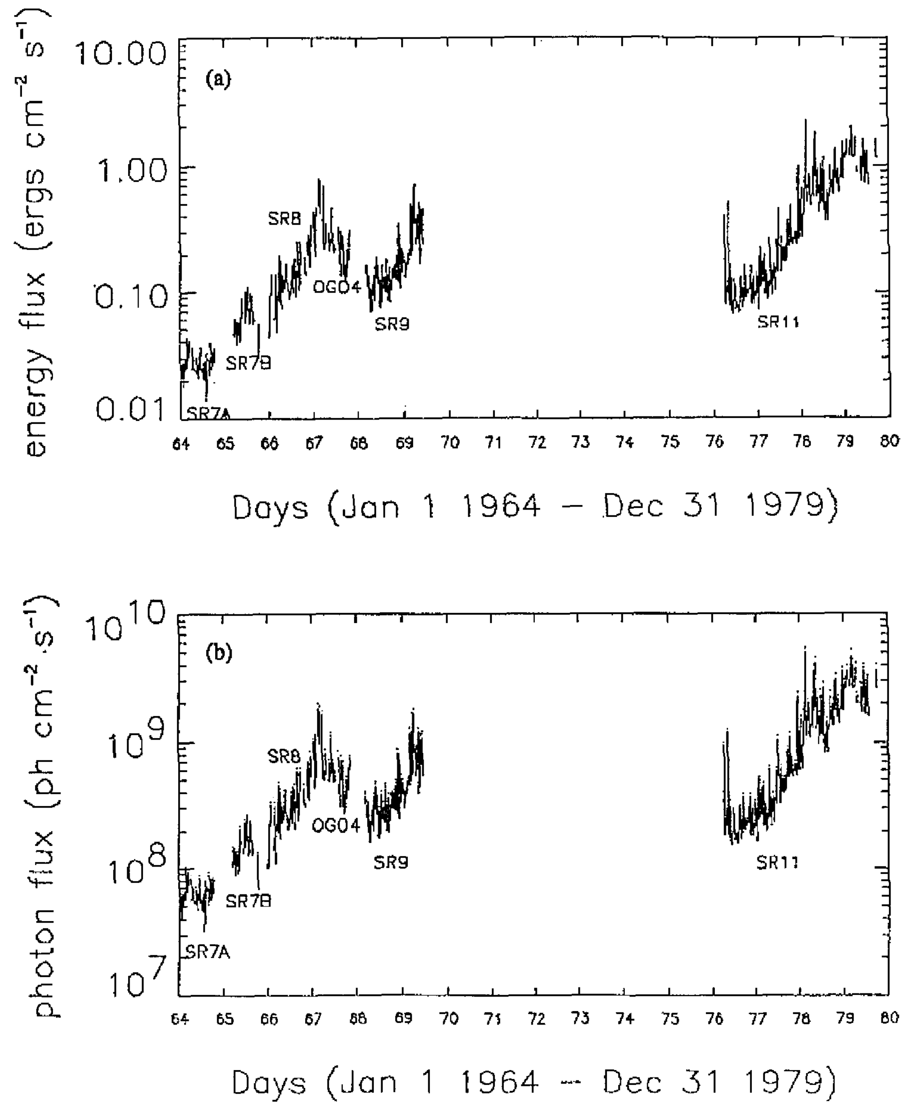

Fig. 2. (a) Daily SR7A, 7B, 8, 9, 11, and OGO4 4.4–6.0 nm energy flux, $E_{44\text{-}60}$, in ergs cm^{-2} s^{-1} between January 1, 1964 and December 31, 1979. (b) Daily derived 3.0–5.0 nm photon flux, $F_{30\text{-}50}$, in photons cm^{-2} s^{-1} $\Delta\lambda^{-1}$ for the same time period and satellite data sets.

where F_{44-60} is the derived SOLRAD 4.4–6.0 nm photon flux. The fraction of the 4.3–5.0 nm photon flux in the SOLRAD bandpass (cf. figure 4, Kreplin and Horan, 1992), A_1, is set to a value of 0.90. It is determined by integrating the digitized bandpass (photometer response) values in the 4.3–5.0 nm interval and then by finding the fractional contribution of that interval (90%) to the total integrated values under the 4.3–5.3 nm curve. Next, the fraction of the photon flux in the 4.3 – 5.0 nm interval compared to the 3.0–5.0 nm interval, B_1, varies from solar minimum to solar maximum conditions. The value used here is determined by an empirical linear relationship where

$$B_1 = p_1 - \frac{F_{10.7} - 68}{175} p_2 \tag{4}$$

where $F_{10.7}$ is the 10.7 cm flux for a given date, 68 is the value of $F_{10.7}$ at solar minimum, and 175 is the range of $F_{10.7}$ values between solar minimum (68) and solar maximum (243). The fractional photon flux between 4.3–5.0 nm for solar minimum, p_1, is 0.86 while the fractional flux for solar maximum, p_2, is 0.07 as determined from the SC#21REFW and F79050N data files provided by Hinteregger *et al.*, (1981). Figure 2 (b) shows the derived SR 3.0–5.0 nm photon flux, F_{30-50}, for the same time period and satellite data as Figure 2 (a).

3. Data – Proxy Correlation and Comparison

A multiple linear regression technique was used to obtain the data and proxy correlation. The same Interactive Data Language (IDL) code used to produce EUV91, described by Tobiska (1991), was also used in this work. The $F_{10.7}$ daily and 81-day mean (F_{81}) values were the independent data sets. These ground-based measurements are representative of the transition region and coronal solar emissions which are also the source layers for the 3.0–5.0 nm flux.

The dependent data were the SR11 measurements. Even though SR7 through SR11 were available, the SR11 data alone were selected for correlation. These data represented low to high solar activity measured by two intercalibrated instruments (SR11A and SR11B were flown at the same time). These instruments (referred to herein as SR11) were the standard to which other SR instruments were compared. The SR11 time frame also allows comparisons between the SR data and HEH data.

Most of the flux in the 3.0–5.0 nm interval comes from solar transition and coronal source regions. From the source region code in the SC#21REFW data file, the small chromospheric component of this wavelength range consists of two unspecified ion lines at 46.67 Å and 47.87 Å. These two lines in the HEH data contributed 37% of the flux in this wavelength interval at solar minimum and 12% of the flux at solar maximum. The coronal component is clearly dominant and therefore the combined source region contributions are modeled using $F_{10.7}$ and F_{81}.

Figure 3 (a) shows the newly modeled 3.0–5.0 nm flux (herein temporarily called EUV93) for the period between 1962 and 1990 while Figure 3 (b) shows the comparison between the SR11 data and the EUV93 values for 500 days during the rise of solar cycle 21. The correlation coefficient, r, between the SR11 and the $F_{10.7}$ data is 0.95

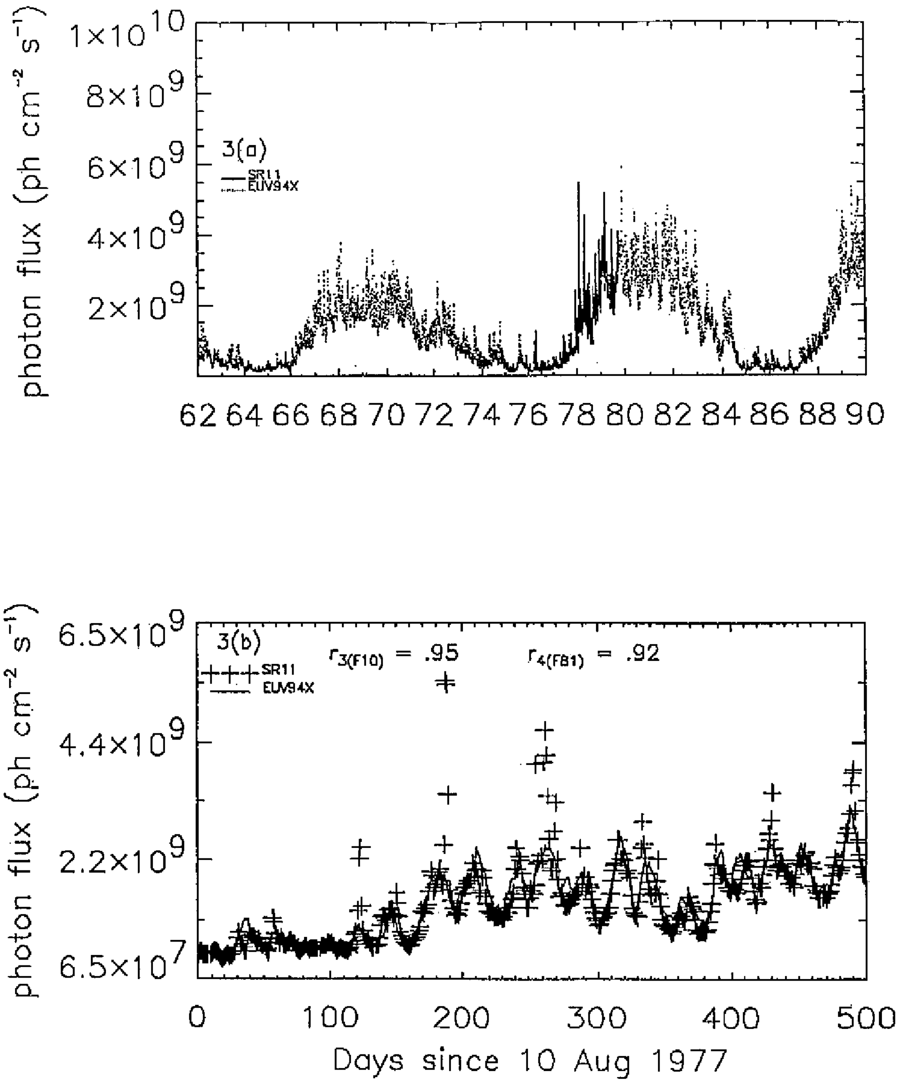

Fig. 3. (a) Daily modeled (EUV93) 3.0–5.0 nm photon flux (combined coronal and chromospheric components) between January 1, 1962 and December 31, 1989 (dots) and SR11 derived data (solid line). (b) Daily EUV93 (line) and derived SR11 3.0–5.0 nm photon flux (plus symbol) for 500 days beginning August 10, 1977.

while r between SR11 and F_{81} is 0.92. The absolute magnitude and the relative solar rotation peak-to-valley variation in EUV93 compares very well with the derived data. A typical EUV93 27-day peak-to-valley ratio is 2.0 while a typical derived data 27-day peak-to-valley ratio is 2.2.

Comparisons between derived data of 3.0–5.0 nm photon flux, the EUV91 model, and the HEH values are shown in Table I. The SR values for solar minimum conditions (76200) are 7.4 times larger than the HEH values and are 27.4 times larger at solar max-imum (79050). These large ratios have produced debate regarding the ratio of derived to measured flux for the two sets of instruments (SOLERS22 meeting, 1993).

TABLE I

Comparison of photon fluxes in the 3.0–5.0 nm interval

Date (YYDDD format)	Data (photons cm^{-2} s^{-1} $\Delta\lambda^{-1}$) origin		
	HEH	EUV91	SR11
76200 (SC#21REFW)	2.3×10^{7}	1.6×10^{7}	1.7×10^{8}
79050 (F79050N)	1.9×10^{8}	1.6×10^{8}	5.2×10^{9}

Figure 4 (a) shows the comparison of the SR11, EUV93, and HEH absolute flux values for the 3.0–5.0 nm interval. Between mid-1977 and mid-1979, during the rise of solar cycle 21, there consistently is an order of magnitude difference between the SR-derived/EUV93 flux and the HEH data. Also, the absolute value of the derived 3.0–5.0 nm flux during the solar cycle rise increased by at least a factor of 10. Figure 4 (b) shows the ratios of these data for the same time frame. The SR11/HEH ratio averages around 27 for most solar activity conditions outside of solar minimum.

The absolute differences between SR11 and HEH data may represent calibration differences between the instruments to be potentially resolved with new data sets such as YOHKOH SXT. The empirical model in this work does not attempt to resolve these absolute differences. Instead, it uses the SR11 data as the primary source, i.e., the dependent data set, to estimate the relative time variability of the 3.0–5.0 nm photon flux using the 10.7 cm daily and 81-day mean proxies.

4. Summary

Improved estimates of 3.0–5.0 nm soft X-ray photon flux relative variation values have been obtained. The estimates were accomplished by digitizing the SOLRAD 11 4.4 to 6.0 nm energy flux data, extracting and extrapolating a derived 3.0 to 5.0 nm photon flux, and by performing a correlation between these derived data and the daily and 81-day mean 10.7 cm radio flux emission using a multiple linear regression technique. The derived 3.0–5.0 nm photon fluxes correlate well with 10.7 cm daily and 81-day mean values with correlation coefficients of 0.95 and 0.92, respectively. The relative variability on 27-day solar rotational time scales during the rise of solar cycle 21 is a factor of 2.2 for the derived 3.0–5.0 nm data.

When comparing the derived SR data and the HEH data, the SR11 derived 3.0–5.0 nm data have ratios near 27 during the rise of solar cycle 21. In addition, the derived

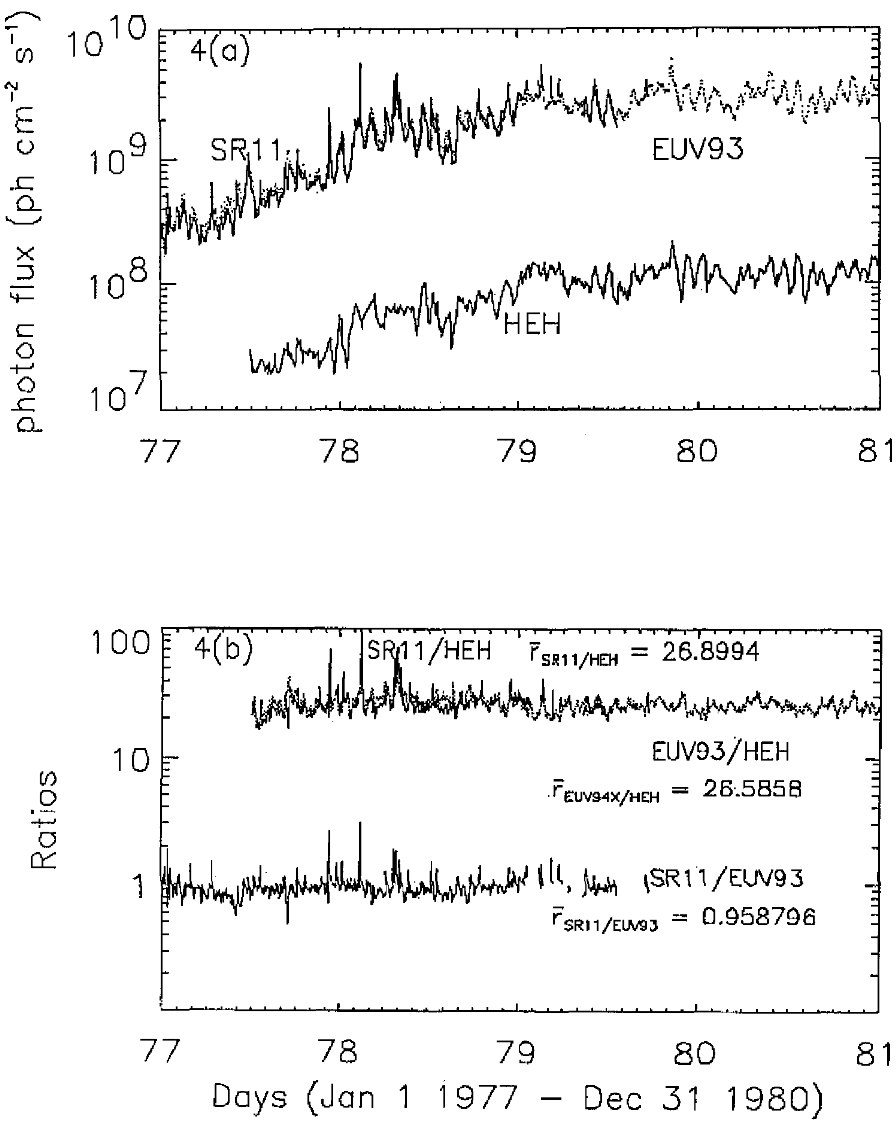

Fig. 4. (a) Daily SR11 (labeled solid line), EUV93 (dots), and HEH (labeled solid line) absolute 3.0–5.0 nm photon flux between January 1, 1977 and December 31, 1980. (b) Daily ratios of SR11 to HEH (labeled solid line), EUV93 to HEH (dots), and SR11 to EUV93 (labeled solid line) for the same time period.

and modeled 3.0–5.0 nm photon fluxes vary by more than an order of magnitude over rising solar cycle activity time scales from 1×10^8 to 1×10^9 photons cm^{-2} s^{-1}.

The revised soft X-ray photon fluxes for all levels of solar activity suggest that important questions in E-region ionosphere and lower thermosphere studies which are related to time-varying solar energy input can be investigated in more detail.

Acknowledgments

Mr. Bill Hoffman and Mr. Paul Fisher of the Jet Propulsion Laboratory Galileo Project provided much appreciated assistance in digitizing the SOLRAD data sets. The author also thanks Dr. Robert Kreplin, Dr. Anatoly Nusinov, and Dr. Frank Eparvier who provided many helpful comments on this work.

References

Barth, C. A., Tobiska, W. K., Siskind, D. E., and Cleary, D. D.: 1988, *Geophys. Res. Letters* **15**, 92.

Hinteregger, H. E., Fukui, K., and Gilson, B. R.: 1981, *Geophys. Res. Letters* **8**, 1147.

Kahler, S. W., and Kreplin, R. W.: 1991, *Solar Phys.* **133**, 371.

Kreplin, R. W.: 1970, *Ann. Geophys.* **26**, 567.

Kreplin, R. W., Dere, K. P., Horan, D. M., and Meekins, J. F.: 1977, in O. R. White (ed.), *The Solar Output and Its Variation*, Colorado Associated University Press, Boulder.

Kreplin, R. W. and Horan, D. M.: 1992, in R. F. Donnelly (ed.), 'Proceedings of the workshop on the solar electromagnetic radiation study for solar cycle 22,' p. 405.

Link, R., Gladstone, G. R., Chakrabarti, S., and McConnell, J. C.: 1988, *J. Geophys. Res.* **93**, 14,631.

Ogawa, H. S., and Judge, D. L.: 1986, *J. Geophys. Res.* **91**, 7089.

Richards, P. G., and Torr, D. G.: 1984, *J. Geophys. Res.* **89**, 5625.

Siskind, D. E., Barth, C. A., and Cleary, D. D.: 1990, *J. Geophys. Res.* **95**, 4311.

Tobiska, W. K.: 1991, *J. Atmos. Terr. Phys.*, **53**, 1005.

Winningham, J. D., Decker, D. T., Kozyra, J. U., Jasperse, J. R., and Nagy, A. F.: 1989, *J. Geophys. Res.* **94**, 15,335.