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Measurements of the solar soft x-ray irradiance from the Student Nitric Oxide Explorer

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Abstract. Beginning on March 11, 1998, the Student Nitric Oxide Explorer (SNOE) satellite has made daily observations of the solar soft x-ray irradiance. These measurements are carried out by a multi-channel photometer system utilizing x-ray sensitive photodiodes with individual thin film filters. Current from the photodiodes is analyzed in terms of a solar reference spectrum in order to determine solar irradiances. The irradiances from 2 to 10 nm vary between 0.15 and 0.40 ergs cm^{-2} s^{-1} from March 11 to July 19, 1998 while the solar 10.7 cm fluxes varied between 85 and 140 $x10^{-22}$ W m^{-2} Hz^{-1}. A 27-day periodicity is observed with variations in the soft x-ray irradiance on the order of a factor of two. The measured irradiances are shown to be correlated with the solar 10.7 cm flux but only mildly so with the GOES-8 0.1 to 0.8 nm solar fluxes.

Introduction

Solar soft x-ray (λ < 30 nm) energy is deposited into the lower thermosphere at altitudes between 100 and 150 km. This radiation photoionizes N_2, O, and O_2 resulting in the production of photoelectrons which further ionize and dissociate molecules. While not the dominant form of energy deposited into the lower thermosphere, solar soft x-rays are the most variable with the exception of auroral energetic particles deposited at high latitudes. Solar soft x-rays are the primary source of photoionization and dissociation of N_2. These facts led Barth *et al*. [1988] and Siskind *et al*. [1990] to suggest that the variability of solar soft x-rays was the source of the large variability observed in low latitude thermospheric nitric oxide densities.

Most of our knowledge of solar soft x-rays and their variability has come from sounding rocket measurements. Discussions of these measurements can be found in Feng *et al*. [1989] and Bailey *et al.* [1999] and their references. A review of the solar soft x-ray irradiance and its variability can be found in Lean [1987; 1991]. Models of the variability of the solar soft x-ray irradiance have been produced by Hinteregger *et al*. [1981] and Tobiska and Barth [1990] as well as others. Lean [1990; 1991] reviews these models. Discrepancies between modeled solar soft x-ray irradiances and magnitudes of irradiance required to bring models into agreement with thermospheric and ionospheric measurements have been found [for example Richards and Torr, 1984; Siskind *et al*., 1990; 1995]. These discrepancies vary with solar activity and upon the type of analysis performed but are typically more than a factor of two for low solar activity [Richards *et al*., 1994].

SNOE was launched on February 27, 1998 into a 556 km near circular sun-synchronous orbit with an average local time of 10:30 AM/PM. It is a spinning satellite rotating at 5 RPM. Details of the mission, the scientific objectives, the spacecraft, its subsystems, and the instrumentation, can be found in Solomon *et al*. [1996] and Bailey *et al*. [1996]. One of the three science instruments on SNOE is designed to measure the solar soft x-ray irradiance from 2 to 20 nm. The goal of this paper is to describe the first results from these solar measurements. A companion paper [Barth *et al*., 1999] uses these results to study the relationship between solar soft x-ray irradiance and thermospheric NO densities also measured by SNOE.

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Instrumentation

The Solar X-ray Photometer (SXP) on the SNOE spacecraft performs photometric measurements of the solar soft x-ray irradiance in 3 wavelength channels. The channels consist of x-ray sensitive photodiodes with thin films deposited directly onto the active areas. Ogawa *et al*. [1990] and Bailey *et al*. [1999] describe solar irradiance measurements using this technique from sounding rockets. The combination of bare photodiode sensitivity, coating materials, and thicknesses of those materials determine the passband for each channel. The SNOE complement of photodiodes includes coatings of 1) titanium, 2) zirconium, titanium, and carbon, and 3) aluminum and carbon. These photodiodes have primary sensitivity in the $\lambda < 10$, $7 < \lambda < 17$, and $17 < \lambda < 20$ nm spectral ranges respectively. For this paper we focus on the titanium (Ti) coated photodiode and wavelengths less than 10 nm. Results from the other channels will be the subject of a later work.

Calibrations of the coated photodiodes were performed prior to launch using the Synchrotron Ultraviolet Radiation Facility (SURF II) at the National Institute for Standards and Technology at wavelengths longer than 5 nm [Canfield, 1987]. In order to enhance the accuracy of the calibrations and extend the wavelength coverage below 5 nm, the sensitivity is modeled based on the known sensitivity of a bare photodiode [Korde and Canfield, 1989; Canfield *et al.,* 1994] and the calculated transmission of the thin film filters. The modeled sensitivity, which agrees with the SURF calibrations to within 5% above 5 nm, is used in the SXP data processing.

Long wavelength (i.e., visible light) contributions to the measured signal are accounted for through the use of a fused silica window. A door mechanism on the SXP moves the fused silica window in front of the photometer channels. Degradation of the fused silica window in space is expected to be minimal; nonetheless, one uncoated SXP photodiode is used to measure the visible transmission of the window. To date, no degradation of the window has been observed.

Analysis

Removal of the visible light contribution to the measured current is accomplished by subtracting a door-closed (i.e., window in front of the photodiode) measurement from a dooropen measurement. The door-closed measurements are first corrected for the measured transmission of the window. These two steps yield a current that is due only to solar soft x-ray irradiance.

The next analysis step is to convert the x-ray current into physical irradiance units. For this conversion a solar reference spectrum and the sensitivity of the photodiode are convolved to produce a reference current. The ratio of the measured current to the reference current is defined as the scaling factor for the reference spectrum over the bandpass of the photodiode (2 to 10 nm for the Ti photodiode). The scaling factor is applied to the reference spectrum and integrated over its bandpass to give the solar irradiance in energy units (ergs cm^{-2} s^{-1}). Energy units are optimal for the SXP results because a silicon photodiode current is proportional to the impinging energy flux (1 electron hole pair per 3.63 eV photon energy). Thus the effect of uncertainties in shape of the reference spectrum are greatly reduced when values of bandpass integrated energy flux are reported.

For the present analysis, the SC#21REFW solar spectrum of Hinteregger *et al*. [1981] is used. This reference spectrum is at a resolution of approximately 0.1 nm. The result of the convolution of the reference spectrum with the sensitivity of the Ti photodiode is shown in Figure 1. The result is shown in units of percent of total current in 1-nm intervals. Thus 32% of the total signal comes from solar irradiance in the 5 to 6 nm interval and 92% in the 2 to 8 nm interval. The figure shows that measured current in this photodiode is produced by solar irradiance below 10 nm. The photodiode is sensitive below 2 nm; however, the reference spectrum goes down only to 1.8 nm.

Uncertainties in the irradiances are due to uncertainties in the calibrations, errors of line ratios in the assumed reference spectrum, and random errors in the measurements. The uncertainties in the calibrations including measurements and the application of the modeled sensitivity are about 10%. The uncertainties due to random errors in the measurements, including the removal of the visible light contribution, are found to be approximately 10%. Errors in the line ratios of the assumed reference spectrum are estimated to affect the irradiance on the order of 5%. This value is obtained by comparing results using different solar reference spectra representative of different levels of solar activity. All of the above uncertainties are 2σ values. The total root-mean-square uncertainty for the measurements is about 15% (2σ).

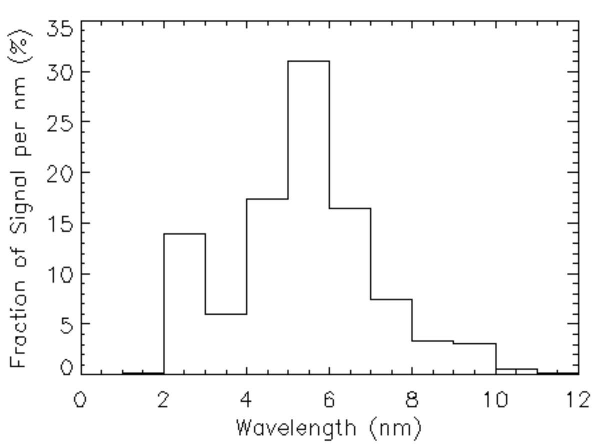

Figure 1. Fractional contribution of current to total current as a function of wavelength assuming the SC#21REFW solar reference spectrum and the modeled sensitivity of the Ti-coated photodiode.

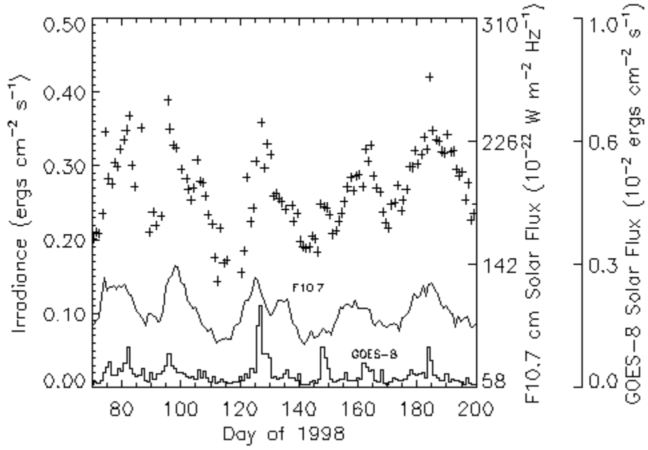

Figure 2. Daily measurements of the solar soft x-ray irradiance (plus symbol) integrated over the 2 to 10 nm spectral interval. The F10.7 cm solar flux and the 0.1 to 0.8 nm flux (histogram) measured from the GOES-8 spacecraft are also shown.

SNOE began making solar measurements on March 11, 1998. The procedure described above is applied to 4 individual solar x-ray measurements per day and averaged to produce a daily result. The daily averaged irradiances for 131 days of the SNOE mission are shown in Figure 2. For this time period, the 2 to 10 nm irradiances from the Ti photodiode are observed to vary between 0.15 and 0.4 ergs cm^{-2} s^{-1}. Results from days 119 and 126 of 1998 are not shown in this time series because the 4 individual measurements on those days were very different from one another and the daily average was more than a factor of 3 times larger than the surrounding days. These differences are likely the result of solar flare activity. Flare activity was searched for in the GOES-8 satellite measurements of the solar 0.1 to 0.8 nm flux. These data are available from the National Geophysical Data Center in daily averages as well as in time resolutions of 5 minutes. The 5-minute data showed fluxes greater than 10^{-4} W m^{-2} during at least one of the four SNOE measurements made on both days 119 and 126. Such high levels occurred only 5 times during the time period of study and lasted for periods on the order of one hour. Only on days 119 and 126 of 1998 did SNOE measurements overlap with these periods of brief enhanced activity. These levels are nearly an order of magnitude higher than any other GOES measurement made during a SNOE measurement. The affects of solar flare activity on SNOE measurements of soft x-ray irradiances will be discussed in detail in an upcoming paper.

The 27-day periodicity due to solar rotation is obvious in the time series. Four minima in the 27-day periodicity can be readily identified near days 90, 115, 142, and 170. Values for the minimum irradiance in each 27-day period are taken from 3 day averages centered about the above days while the values for the maximum in each 27-day period are taken from 3 day averages centered about days 95, 128, 165, and 185 respectively. The ratio of the peak irradiances to values in the preceding minima are 1.9, 2.1, 1.7, and 1.6. Thus 27-day variability in solar soft x-ray irradiances is on the order of a factor of two. As more SNOE data becomes available, many more solar rotations will be observed and the nature of the 27 day variability and its variation during the rise to solar maximum will be observed.

During the time period between March 11 and July 19, 1998, the solar 10.7 cm radio flux (F10.7) varied from about 85 to 140 $x10^{-22}$ W m^{-2} Hz^{-1}. The daily F10.7 values are shown in

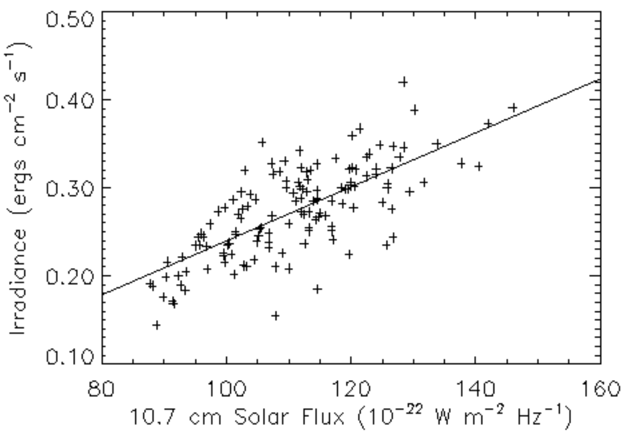

Figure 3. Daily measurements of the solar soft x-ray solar irradiance integrated over the 2 to 10 nm spectral interval plotted as a function of the daily F10.7 cm solar flux.

Figure 2 along with the SNOE measurements. Also shown in Figure 2 are the GOES-8 0.1 to 0.8 nm solar fluxes. A similar 27-day periodicity is shown in each of the time series. The 0.1 to 0.8 nm fluxes are significantly more variable, by nearly an order of magnitude, than both the F10.7 and the SNOE 2 to 10 nm irradiances.

The daily 2 to 10 nm irradiances described above are plotted versus the daily F10.7 values in Figure 3. This figure shows a correlation between F10.7 values and 2 to 10 nm irradiances. A linear fit of daily average irradiances to F10.7 values is also plotted in the figure. The calculated correlation coefficient for this fit is 0.68. This correlation is likely to improve for a longer data set as these initial results cover only a limited range of solar activity. The slope of the line is 0.0031 ergs cm^{-2} s^{-1} per F10.7 value. Assuming that the linear correlation extends to solar minimum, then the linear fit predicts a solar minimum value of 0.14 ergs cm^{-2} s^{-1} for the solar minimum F10.7 value of 68. This result compares well (higher by 17%) with the value of 0.12 ergs cm^{-2} s^{-1} predicted by the SC#21REFW reference spectrum. This result is surprising given that several works [e.g., Barth *et al*., 1988; Siskind *et al*., 1990, and Richards *et al*., 1994] have suggested that at least a factor of two discrepancy exists between the reference and the true irradiances. This fit is appropriate only to irradiances measured during the low to moderate solar activity during these 131 days of the SNOE mission. As solar activity increases, the variation of solar soft x-ray irradiances with F10.7 will be better quantified.

A similar fit was performed between the SNOE 2 to 10 nm measurements and the GOES 0.1 to 0.8 nm measurements. A correlation coefficient of 0.43 was found. This result shows that the solar soft x-ray irradiance is significantly better correlated with the F10.7 index compared to the GOES measurements.

There is much more analysis to be performed and presented in our future work. The other SXP photodiodes indicate similar results but with less variability. This reduced variability is expected because their bandpasses are at longer wavelengths. We are examining the differences in the derived irradiances using different reference spectra as well as proxy models of solar soft x-ray irradiances in order to validate and possibly improve the SXP irradiances. These SXP results will also be used for the analysis of the SNOE NO measurements and for the development of improved solar soft x-ray proxy models.

Summary

We have presented a time series of solar 2 to 10 nm irradiance measurements made from the SNOE satellite. These measurements cover the time period from March 11 to July 19, 1998. The irradiances are observed to vary between 0.15 and 0.40 ergs cm^{-2} s^{-1} while the solar 10.7 cm fluxes varied between 85 and 140 x10^{-22} W m^{-2} Hz^{-1}. A 27-day periodicity is seen in the data. The 27-day variations are on the order of a factor of 2. The data are correlated with the F10.7 index but only mildly so with the GOES 0.1 to 0.8 nm fluxes. A detailed comparison to other measurements in the same wavelength region has not yet been done; however, we note that the solar minimum irradiance value obtained through extrapolation of this data set to solar minimum conditions is in good agreement with a commonly used reference spectrum. This result is surprising given that other works have shown that this reference spectrum does not provide enough energy deposition to account for observations of the Earth's atmosphere.

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