

Effect of solar soft X-rays on the lower ionosphere

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Abstract. New measurements of solar irradiance in the soft X-ray region of the spectrum from the SNOE satellite [Bailey *et al.*, 2000] show that the full-disk solar irradiance in the ~ 2 –20 nm region is higher than a standard model [Hinteregger *et al.*, 1981] by a factor of ~ 4 at all levels of solar activity. This confirms contentions developed from several lines of evidence, [e.g., Richards and Torr, 1984; Richards *et al.*, 1994] but to a larger degree than previously suspected. This finding has many implications for the thermosphere and ionosphere, two of which are examined here. Greatly improved agreement between measurement and model of the photoelectron spectrum is obtained when the solar soft X-ray input is adjusted to the SNOE measurements. We also found good agreement between electron density profiles measured by the incoherent scatter radar at Millstone Hill [Buonsanto *et al.*, 1992] and our model, solving a fundamental problem identified in that work.

Introduction

The soft X-ray to hard extreme-ultraviolet region of the solar spectrum from 1–30 nm, sometimes designated “XUV,” has been difficult to quantify. Although the reference spectrum and scaling factors obtained from the Atmosphere Explorer (AE) program and from rocket measurements by Hinteregger *et al.* [1981] has been considered an acceptable standard in the extreme ultraviolet (EUV) from ~ 30 to ~ 103 nm, there is considerable doubt concerning its validity shortward of ~ 25 nm. The problem dates back to comparisons with AE photoelectron measurements by Richards and Torr [1984], and is reviewed by Solomon [1991] and Bailey *et al.* [2000].

Solar XUV photons are few in number, but they are energetic, variable, and important for production of photoelectrons, *E*-region ionization, thermospheric odd-nitrogen, and daytime airglow emissions. They deposit their energy throughout the thermosphere, but especially in the altitude range from 100 to 200 km. Broad-band ionization cell and photodiode measurements [Feng *et al.*, 1989; Ogawa *et al.*, 1990; Bailey *et al.*, 1999a] have indicated that the Hinteregger *et al.* [1981] model underestimates solar XUV fluxes. The factor of ~ 3 increase in the Hinteregger *et al.* solar XUV

flux below 25 nm proposed by Richards and Torr [1984], has been generally supported by the few available measurements, and also by photoelectron data from the Dynamics Explorer-2 satellite [Winningham *et al.*, 1989].

Other evidence points in the same direction, including airglow analyses, calculation of nitric oxide densities, and modeling of the lower ionosphere. Work by Buonsanto *et al.* [1990, 1992, 1995] found a significant shortfall in models of the *E* and *F*₁ region ionosphere between 100 and 200 km, when compared to incoherent scatter radar and ionosonde measurements. Because XUV photons produce additional ionization by photoelectron impact ionization of neutral species, the photoelectron and ion density problems are intertwined in the lower ionosphere. The purpose of this letter is to apply new information concerning the solar XUV irradiance to these issues.

Solar Soft X-ray Observations

The Student Nitric Oxide Explorer (SNOE) satellite and instrumentation are described by Solomon *et al.* [1996] and Bailey *et al.* [1996]. Preliminary results from the first 4 months of the mission were given by Barth *et al.* [1999], Bailey *et al.* [1999b], and Solomon *et al.* [1999]. The first 1.5 years of solar X-ray data, the measurement and calibration method, its accuracy and precision, and results from a rocket flight intercalibration, were presented by Bailey *et al.* [2000, 2001].

The SNOE solar X-ray photometer (SXP) performs measurements of the solar irradiance in broad wavelength bands. Each channel consists of an X-ray sensitive silicon photodiode with a thin metallic film deposited directly onto the active area. The 3 primary SNOE channels cover spectral ranges from approximately 2–7, 6–19, and 17–20 nm. During the period shown here, solar measurements were performed ~ 4 times per day. The photodiodes were calibrated prior to launch using the NIST Synchrotron Ultraviolet Radiation Facility. A rocket measurement of the solar soft X-ray irradiance on November 2, 1998 was also performed, to validate the SNOE observations and to check for any on-orbit degradation. Good agreement was obtained between the orbital and sub-orbital measurements.

Measurements by the SNOE SXP during the ramp-up of solar cycle 23 are shown in Figure 1. These are daily average values, with any obvious flare activity removed. Solar activity ranged from moderately low to high during this period ($F_{10.7}$ varied between 89 and 253). Also shown on

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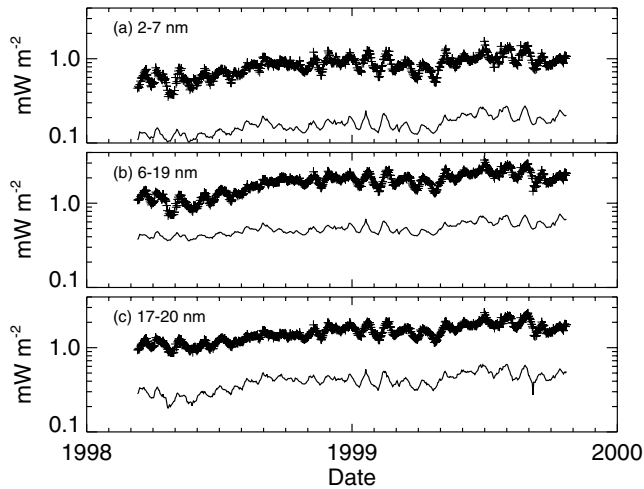


Figure 1. Measurements of the solar soft X-ray flux in three photometric channels: a) Ti/TiO channel from 2 to 7 nm; b) Zr/Ti/C channel from 6 to 19 nm; c) Al/C channel from 17 to 20 nm. Plus symbols: daily average measurement by the SNOE SXP. Solid line: *Hinteregger et al.* [1981] model.

the plots are fluxes in each bandpass predicted by the *Hinteregger et al.* [1981] model for each day, using the $F_{10.7}$ association method to scale the “SC#21REFW” reference spectrum. Comparison is facilitated by plotting the ratio of measurement to model, as shown in Figure 2. The 81-day average of the ratio is also shown on these plots. In all three wavelength ranges, the measurements are considerably higher than the model. The average ratios for March 1998 through October 1999 are 5.0 at 2–7 nm, 3.5 at 6–19 nm, and 4.4 at 17–20 nm. A 27-day modulation can be seen in the ratios, indicating that the model slightly underestimates the rotational variability, but the relative magnitude of the solar cycle variability is adequately represented.

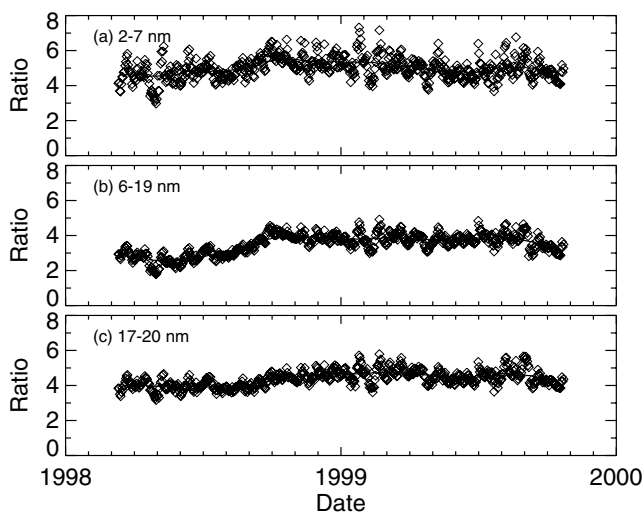


Figure 2. Ratio of the daily average SNOE SXP measurement to the *Hinteregger* model: (a) Ti/TiO channel from 2 to 7 nm; (b) Zr/Ti/C channel from 6 to 19 nm; (c) Al/C channel from 17 to 20 nm. Diamonds: daily average measurements. Solid line: 81-day average.

Ionospheric Model

Ionization rates, photoelectron fluxes, and ion/electron densities are calculated using the *glow* model [*Solomon et al.*, 1988; *Solomon and Abreu*, 1989]. The neutral atmosphere is specified by the MSIS-86 semi-empirical model [*Hedin*, 1987]. The *Hinteregger et al.* [1981] solar irradiance model is used as the energy input. SNOE SXP measurements were incorporated using an elementary approach: the *Hinteregger et al.* spectrum was increased by a factor of 4 shortward of 25 nm. Although there is arguably some spectral variation in the appropriate scaling, we make this simple assumption for our preliminary study.

The lifetimes of ions and electrons in the 100–200 km region are on the order of a minute, so transport of the ambient ionosphere is nearly negligible. Thus, a photochemical equilibrium model is valid. There are some exceptions to this: rapid vertical motions or long-lived metallic ions can make transport processes significant, and above ~ 180 km, at low solar activity, vertical diffusion can begin to come into play. These processes are not included here, but photoelectron transport is included at all model altitudes. *K*-shell ionization and consequent Auger electrons are included in the model, to fully account for ionization caused by solar photons shortward of 3 nm.

Comparison with Measurements

An energy spectrum measured by the AE Photoelectron Spectrometer (PES) is selected for comparison from those published by *Lee et al.* [1980]. It was obtained near 167 km altitude at low solar activity, early in the AE-E mission. This spectrum is chosen for an initial comparison because it is the same spectrum used by *Strickland et al.* [1999] to validate the AURIC model. *Strickland et al.* found reasonable agreement if the *Hinteregger et al.* [1981] solar spectrum was increased by a factor of 2.0 below 25 nm and the photoelectron spectrum was scaled downward by a constant factor

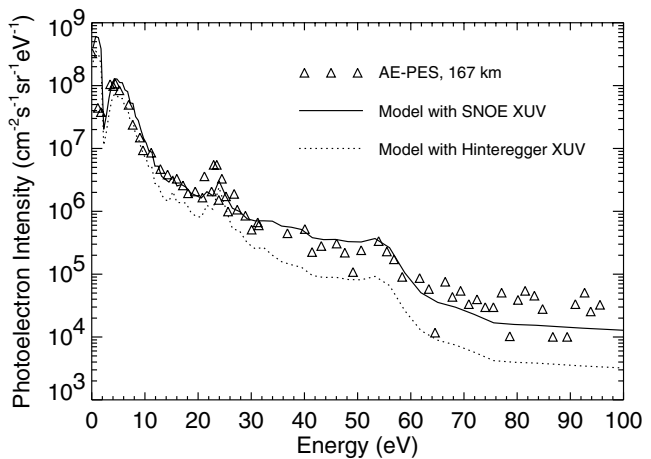


Figure 3. Comparison of measured to modeled photoelectron fluxes at 167 km altitude on 25 January 1976 at 01:57 UT. The latitude was 10°N , longitude 93°E , and the solar zenith angle 66° . The $F_{10.7}$ index was 70 and its 81-day average was 75. Triangles: measurements by the PES on AE-E. Solid line: model using the *Hinteregger et al.* [1981] solar flux model as input, but multiplied by a factor of 4 below 25 nm to match the SNOE SXP measurements. Dotted line: model using unscaled *Hinteregger et al.* solar flux.

of 0.67 [Conway, 1983]. There is generally good agreement between the *glow* and AURIC model photoelectron fluxes for the same solar and atmospheric inputs.

Figure 3 shows the comparison between the AE-PES measurement and two runs of the same model. In the first run, the *Hinteregger et al.* [1981] model solar spectrum was employed. In the second, the same solar spectrum is used, but multiplied by a factor of 4 shortward of 25 nm to approximate the SNOE measurements. The model with increased solar XUV is a much better match for the data. Some discrepancies remain, for instance at the features near 25 eV caused by the intense solar He II line at 30.4 nm. Above 70 eV, the measurements are noisy and probably unreliable, so the lack of fit there should not be considered meaningful. Nevertheless, a further increase in the solar spectrum shortward of 10 nm could be supported by both the solar and photoelectron measurements.

Model electron density profiles are compared to measurements by the Haystack Observatory incoherent scatter radar at Millstone Hill. These measurements, first published by *Buonsanto et al.* [1992], were intercalibrated with ionosonde measurements. In Figure 4, comparison of measurements near solar minimum to the model using the *Hinteregger et al.* solar spectrum, and using the fourfold increase shortward of 25 nm, is shown. This result is comparable to Figure 9 of *Buonsanto et al.*, but the increased XUV irradiance obtains a much better match to the observed electron density profile. There are two aspects of the observations that are not replicated by the model: the wave-like vertical structure, and the increase in density above 180 km. The former may be due to neutral atmosphere or ionospheric structure that is not captured by a semi-empirical model of atmospheric climatology or by a photochemical equilibrium model. The latter is evidence of diffusive transport of O^+ , which starts to become important at altitudes slightly below 200 km at low solar activity, and is not accounted for in this model formulation.

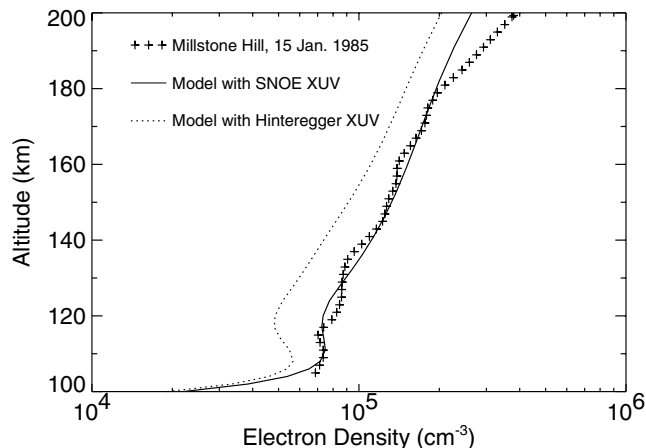


Figure 4. Electron density profiles measured by the MIT Haystack Observatory incoherent scatter radar at Millstone Hill during solar minimum conditions on 15 January, 1985 at 18:15 UT. The $F_{10.7}$ index and its 81-day average were both 72. Plus symbols: radar measurements. Solid line: model using the *Hinteregger et al.* [1981] solar flux model as input, but multiplied by a factor of 4 below 25 nm to match the SNOE SXP measurements. Dotted line: model using unscaled *Hinteregger et al.* solar flux.

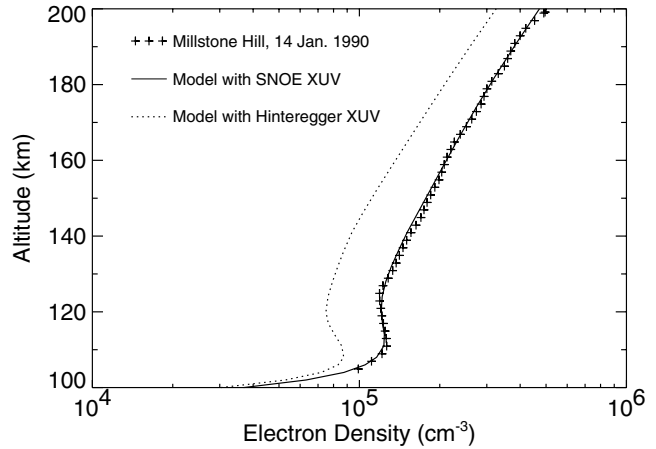


Figure 5. Electron density at Millstone Hill during moderately high solar activity conditions on 14 January, 1990 at 15:57 UT. The $F_{10.7}$ index was 166 and its 81-day average was 193. Plus symbols: radar measurements. Solid line: model using the *Hinteregger et al.* [1981] solar flux model as input, but multiplied by a factor of 4 below 25 nm to match the SNOE SXP measurements. Dotted line: model using unscaled *Hinteregger et al.* solar flux.

A moderately high solar activity comparison is given by Figure 5. The same data presented in Figure 10 of *Buonsanto et al.* [1992] are shown. Excellent agreement is obtained throughout the altitude range when increased solar XUV irradiance is employed in the model.

Discussion

These comparisons provide compelling evidence for a \sim fourfold increase in the *Hinteregger et al.* [1981] model spectrum $< \sim 25$ nm, even if the good agreement between model and measurement were partly fortuitous. Both the neutral atmosphere and the solar irradiance on these particular days could be considerably different from our model estimates. However, variations in neutral density only serve to shift the electron density altitude profile a few kilometers vertically, and do not change the overall amount of ionization. The solar flux may indeed be different from our model estimates at these times, particularly at high solar activity, but the enormously improved agreement obtained by this reformation of the solar XUV supports our contention that the new solar measurements are correct.

The case for this increase, first stated by *Richards and Torr* [1984], is thus a strong one. At the shortest wavelengths, further increases may be indicated. The XUV is dominated by coronal emission lines, and is hence the most intrinsically variable and unpredictable region of the spectrum, so it is unsurprising that it has remained controversial. Recent semi-empirical [*Richards et al.*, 1994; *Tobiska and Eparvier*, 1998] and theoretical [*Warren et al.*, 1998] models have supported an increase in the solar XUV, although not as large as seen by *Bailey et al.* [2000].

These findings have sweeping implications for thermosphere/ionosphere physics. In addition to ionization rates, dissociation rates of both N_2 and O_2 are increased, affecting the odd-nitrogen and odd-oxygen chemistry in the lower thermosphere and mesopause regions. Airglow excitation rates, particularly those processes driven by photoelectron

impact, are increased, which has implications for methods that use remote sensing of airglow emissions to infer thermospheric density and composition. The effect on total heating rates is not large, since solar far-ultraviolet dominates the heating of the lower thermosphere, but it is not negligible, and its variability increases. These issues, and a more comprehensive comparison with photoelectron and ambient electron measurements, will be examined in subsequent work.

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