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Calculating solar UV spectral irradiance using observed spectral radiance and full disk Ca II K images

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Abstract. An empirical model of solar UV spectral irradiance has been developed at the Naval Research Laboratory. This model uses observed spectral radiance measurements from the HRTS-9 rocket and the UV spectrograph on SKYLAB in conjunction with full disk Ca II K images to identify various solar surface features on order to estimate the full disk irradiance. The initial wavelength coverage was a narrow range (180 Å) near the Mg II doublet at 2800 and was derived from HRTS-9 spectral observations. This range is being expanded to cover from roughly 2000 to 4000 using SKYLAB data and future plans include the extension of this range down below 1000 Å.
Currently the model identifies three surface features: quiet sun, active sun, and sunspots. The model requires detailed knowledge of the center-to-limb variation (CLV) of these three features. Originally, the CLV was only available for the quiet sun and so this is now used for all three features. However, we will be examining other data and theoretical sources of CLV for active regions and sunspots. Since the spectral radiance observations are from film data, calibration required the use of irradiance spectra on a set of extremely quiet days from the SUSIM and SOLSTICE instruments on the UARS satellite. Currently, the model has concentrated on the time period between 1990 through 1995 but this is being expanded toward the present in order to extend the comparison between model and observed (UARS) spectra.
This paper is a review of the model that will include the latest understanding of the CLV of the quiet sun, the methods of calibration, and the identification of the above surface features. Future plans to utilize the recently digitized film archives of Ca II K images, such as Mt Wilson, and the Observatories of Rome and Paris, will also be discussed in addition to the planned methods to model the spectrum into the EUV.

Key words. Sun: irradiance – Sun: atmospheres

1. Introduction

Recent efforts to produce estimates of total and spectral solar irradiance that occurred during the last several centuries have relied on sun spot records, the aa geomagnetic index, and time profiles of cosmogenic isotopes from tree rings (^{14}C)and ice cores (^{10}Be). Although these methods have varying levels of reliability they still suffer from uncertainty especially with respect to spectral irradiance (Frohlich and Lean 2004). This paper discusses the development of a model to estimate the solar spectral irradiance in the 2000 to 4000 Å range based on Ca II K images and observed spectra of quiet sun, active sun, and sunspots. The spectra were measured by the HRTS-9 rocket and the SO82A spectrograph on SKYLAB and we are currently examining several sets of Ca II K images observed with electronic detectors.

Once completed, this model will be used to estimate solar spectral irradiance and the Mg II index (Vierick et al. 1995) back to at least the early 1900's by using Ca II K images that were originally recorded on film and are currently being converted to digital form. Several data archives exist such as the images at Mt Wilson Observatory, the Observatory of Rome, and the Observatory of Paris. This paper will discuss the details of the model and preliminary results that have used full disk Ca II K images from Big Bear Solar Observatory (BBSO) (Lean et al. 1998) and spectra from the SUSIM-UARS instrument (VanHoosier 1996).

2. Details of the Irradiance Model

The current full disk irradiance model is a three component model that uses observed spectra from quiet sun, active regions and sunspots as well as center-to-limb variation (CLV) all at high resolution (0.015 Å). The mathematical formulation of this model is shown by the following formula,

$$
\begin{aligned}
F_{FD}(\lambda) = (&\Sigma_{i(QS)} B_{QS}(\lambda) CLV(\lambda, r(i)) + \\
&\Sigma_{j(AR)} B_{AR}(\lambda) CLV(\lambda, r(j)) + \\
&\Sigma_{k(SS)} B_{SS}(\lambda) CLV(\lambda, r(k))) dA \qquad (1)
\end{aligned}
$$

where F_{FD} (λ) is the full disk solar irradiance, $B_{QS}(\lambda)$ is the disk center quiet sun brightness, $B_{AR}(\lambda)$ is the disk center active region brightness, $B_{SS}(\lambda)$ is the disk center sunspot brightness, CLV(λ,r) is the quiet sun limb CLV, and dA is the angular size of the Ca II K pixels (generally 1 arc-second). The wavelength coverage is 2760 to 2880 Å for the HRTS-9 spectra and about 2000 to about 4000 Å for the SKYLAB spectra.

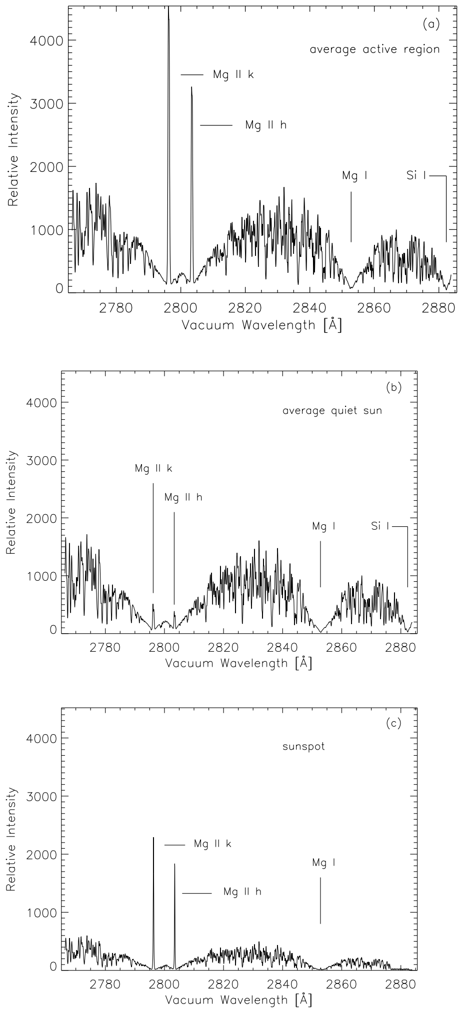

Fig. 1. Spectra derived from HRTS-9 and used for the irradiance model, (a) active sun spectrum, (b) quiet sun spectrum, and (c) sunspot spectrum.

The model uses the full disk Ca II K image of the sun that has been corrected for flat fielding and for the center-to-limb variation of Ca II K. A histogram is determined for each image. The central quiet sun portion is fit with a gaussian and the upper and lower thresholds are determined as the points where the gaussian drops to 10^{-5} of a solar disk.

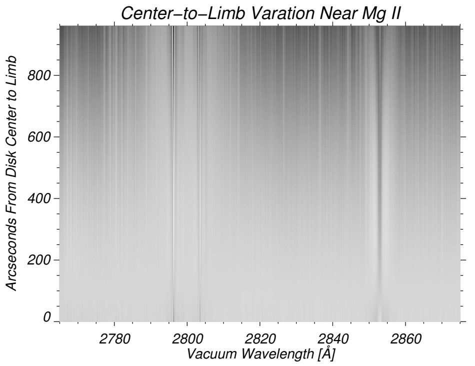

Fig. 2. Center-to-limb variation (CLV) for the quiet sun derived from HRTS-9.

3. Input UV Spectra, CLV, and Ca II K Images

The spectra of the three solar surface features considered in this model were derived from measurements made by the HRTS-9 spectrograph that flew on April, 18, 1995. The derivation of these spectra was presented elsewhere (Morrill et al. 2001) and the three are shown in Fig. 1. Spectrograms from this flight were also used to derive average spectra and CLV in the wavelength region around the Mg II h & k doublet at 2800 Å. Here a spectrogram aligned to observe the quiet sun center-to-limb variability was used to produce polynomial fits to the spectral variations at nearly full resolution (about 0.03 Å). The quiet sun CLV is shown in Fig. 2. The above spectra were calibrated using the CLV curves and spectra observed by the SUSIM and SOLTICE instruments on UARS on several days where the sun is extremely quiet.

The current model results use a set of Ca II K images from BBSO which have been corrected for flat field variations and CLV for Ca II K. The model calculates a histogram distribution of the Ca II K intensity which has a Gaussian central peak that is produced by the quiet sun, a shoulder at higher intensities is produced by the active region plage, and a lower level shoulder that is produced by sunspots. Examples are shown below.

4. Model Results: Spectra and the Mg II Index

Two examples of the output of our model are presented Fig. 3 and Fig. 4. The top-left panels shows the corrected Ca II K image, the top-center shows the histogram distribution of the Ca II K intensity plotted on a log scale, and the top-right panels show the resulting estimated spectra. The bottom row of Fig.s 3 and 4 show a closeup of the estimated Mg II h and k lines at full resolution, a comparison between the SUSIM full disk irradiance spectrum and the estimated spectrum with the resolution degraded to that of the SUSIM spectrum (1.5 Å), and the difference between the SUSIM and estimated spectra.

Fig. 3 shows one of the days used for calibration and the histogram of Ca II K intensity shows that the emission is almost entirely quiet sun. The difference between the two spectra (lower right panel) shows mostly noise which is likely due to slight difference in the wavelength scales of the two spectra. Fig. 4 shows a day of increased activity. Here the active region portion of the histogram has increased significantly and the presence of a few sunspots can be seen as well. The difference shows similar noise but the presence of a negative offset in the region of the Mg II h and k lines is significant and implies a correction to the active region spectra may be needed. We are currently considering ways to improve the agreement in this region.

Once these estimated spectra are calculated a Mg II index can be derived and compared to the NOAA Mg II index. Since these spectra are at higher resolution than those used to calculate the NOAA composite Mg II index (Vierick et al. 1995) a linear fit is performed between the values derived from the estimated spectra and the NOAA index. This fit is then applied to the estimated values and the resulting comparison appears in Fig. 5. Fig. 6 show the two indices over plotted and indicate the estimated values do a reasonable good job reproducing the NOAA index.

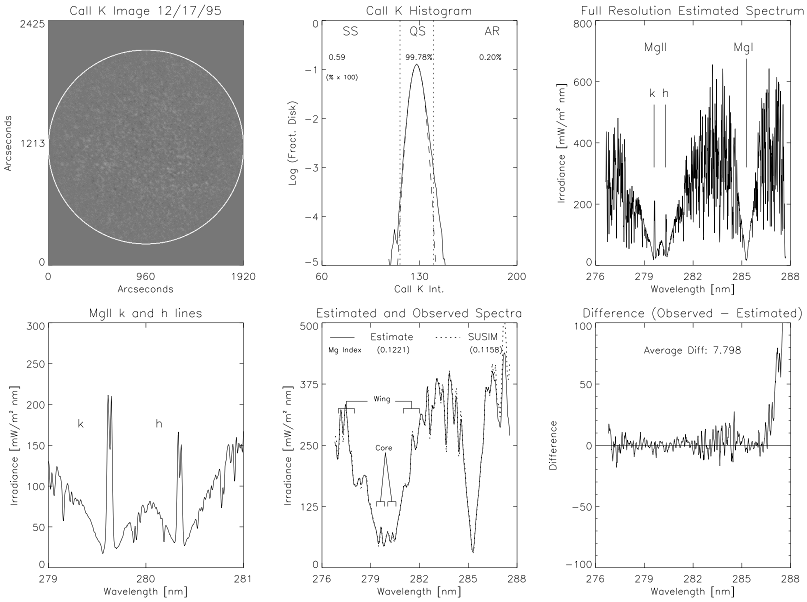

Fig. 3. Model results for extremely quiet day. Panel from left to right, top to bottom are (a) Ca II K image, (b) Ca II K intensity histogram, (c) estimated spectrum at full resolution, (d) blowup of the region near Mg II h and k lines, (e) comparison of estimated spectrum and SISUM-UARS spectrum for this day, and (f) difference between spectra in (e).

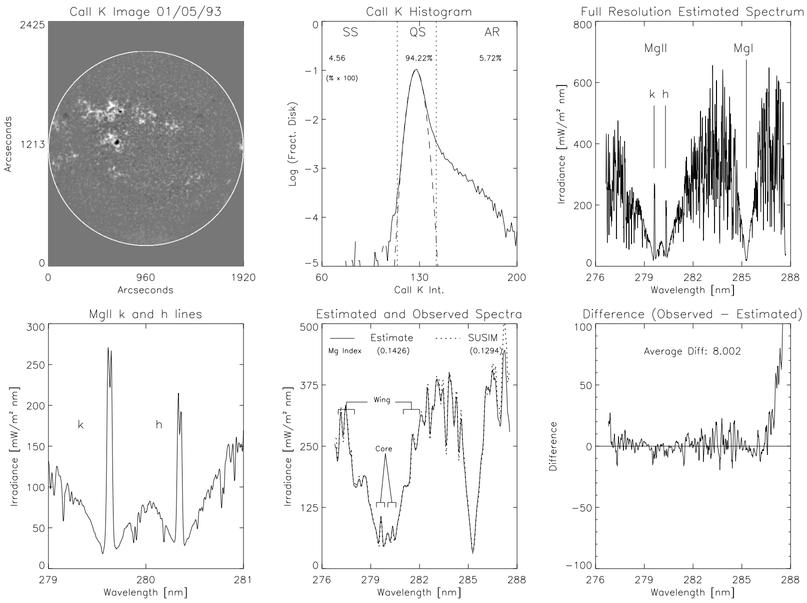

Fig. 4. Same as Figure 3 except for day of increased activity.

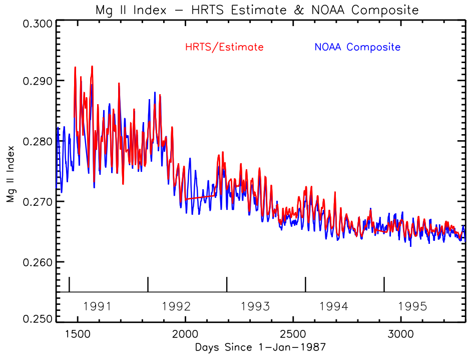

Fig. 6. Time dependent NOAA composite with estimated Mg II index over plotted.

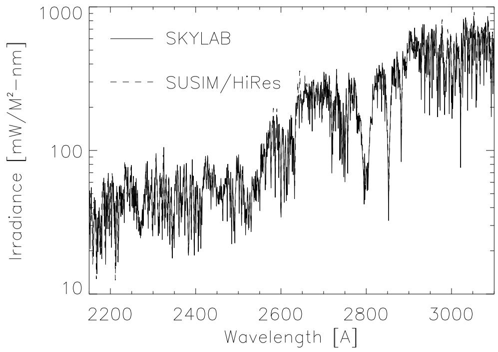

Fig. 7. Estimated quiet sun full disk irradiance compared to SUSIM-UARS spectrum on same day as Figure 3.

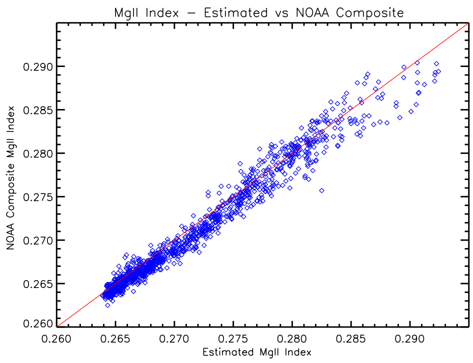

Fig. 5. Correlation between NOAA composite Mg II index and estimated Mg II index with linear fitting applied.

5. SKYLAB Results and Future Efforts

The most recent efforts have involved the analysis of spectral data from the SKYLAB S082A spectrograph. With this data we will expand the spectral range of the model from 2000 to 4000 Å. At present, spectra and CLV for SKYLAB quiet sun observations have been derived from 2100 to 3200 Å and efforts are underway to extend this range to the full 2000 to 4000 Å range and to add spectra from active regions and sunspots. The disk center radiance from SKYLAB is presented in Fig. 7 which compares the estimated spectrum to the radiance derived from SUSIM and the SKYLAB CLV.

Other future efforts include the expansion of the spectrum to wavelengths below 1000 Å. This will involve studying correlations between the Mg II index and observed EUV emissions as well as additional SKYLAB observations at wavelengths below 1000 Å. Also, we plan to utilize Ca II K images from recently digitized film archives such as Mt Wilson, the Rome Observatory, and the Paris Observatory.

6. Conclusions

In this paper we have presented the details of a relatively simple irradiance model and the initial results. These results include estimated full disk irradiance spectra for a number of sample days and the time series of the Mg II index derived from estimated spectra. Comparisons between estimated spectra and observations from the SUSIM-UARS instrument show good agreement over most of the wavelength range. Differences in the region near the Mg II h and k line cores will be examined and may indicate the nead to use a slightly modified active region spectrum. Comparison of the estimated Mg II index with the NOAA composite Mg II index showed a good correlation and that most of the detailed variation of the NOAA index were recovered by the estimated index. Spectra from SKYLAB will soon increase the model wavelength range from 2000 to 4000 Å although current SKYLAB quiet sun spectra range from 2100 to 3200 Å. Future plans include the expansion of the of the wavelength range below 1000 and the use of recently digitized film archives of Ca II K images that will extend our estimated spectra back to the early 1900's and possibily the late 1800's.

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