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Advances in Space Research 35 (2005) 365–369

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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Reconstruction of the solar UV irradiance back to 1974

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Received 1 November 2004; received in revised form 14 April 2005; accepted 17 April 2005

Abstract

The variability of the solar UV irradiance has strong effects on the terrestrial atmosphere. In order to study the solar influence for times when no UV observations are available, it is necessary to reconstruct the variation of the UV irradiance with time on the basis of proxies. We present reconstructions of the solar UV irradiance based on the analysis of space-based and ground-based magnetograms of the solar disk going back to 1974. With COde for Solar Irradiance (COSI) we calculate solar intensity spectra for the quiet Sun and different active regions and combine them according to their fractional area on the solar disk, whereby their time-dependent contributions over the solar cycle lead to a variability in radiation. COSI calculates the continuum and line formation under conditions which are out of local thermodynamic equilibrium (non-LTE). The applied temperature and density structures include the chromosphere and transition region, which is particularly important for the UV. The reconstructions are compared with observations.

Keywords: Solar UV spectrum; Solar activity; Radiative transfer model; Non-LTE

1. Introduction

It is known that the variability of the solar UV irradiance has a considerable effect on the terrestrial atmosphere. Recently, Egorova et al. (2004) have shown that the introduction of solar UV flux into a spectral Global Circulation Model (GCM) with a chemistry transport model leads to an intensification of the polar vortex and a statistically significant warming of up to 1.2 K over North America and Siberia. Due to a missing longterm record of the solar UV irradiance with a sufficient temporal resolution, their study compares the condition at solar maximum with solar minimum. An interesting question now arises how the terrestrial atmosphere responds to a transient change of the UV irradiance. This, however, can only be answered if a longterm data set of the solar UV variability is available. The aim of this work is to provide a reconstruction of the solar UV irradiance for times when no UV observations are available.

Previous attempts to reconstruct the variability of the solar UV irradiance over decades to centuries were carried out by Lean (2000), who extend in time the wavelength-dependent parameterization of the spectral irradiance variability derived from contemporary measurements by using historical estimates for facular brightening and sunspot darkening. Krivova and Solanki (2005) use SUSIM UV observations to extrapolate synthetic spectra to shorter wavelengths and then reconstruct the UV on the basis of magnetograms. Fox et al. (2004) calculate synthetic spectra with a plane-parallel non-LTE radiative transfer code and reconstruct the solar variability on images and

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0273-1177/$30
doi:10.1016/j.asr.2005.04.039

magnetograms that represent solar surface activity features. However, a longterm reconstruction of the UV on a daily basis for more than a decade back in time is not available.

Our approach is that we calculate theoretical intensity spectra for different active regions on the Sun in spherical geometry and reconstruct the UV variability on the basis of magnetograms. Here, we address the reconstructions from 1974 to 2002 which is tested on data from SUSIM. As the main goal of this work is to give an input for GCMs, and the dynamic of the Earth's atmosphere does not respond to a shortterm variability, we focus here on the variability of the solar UV spectrum on time scales of weeks to years, and leave the shortterm variability from days to minutes, caused by flares or spicules, aside.

In the following section, we describe our approach to the reconstruction of the solar UV irradiance. In Section 3, the radiative transfer code COSI is described, and in Section 4, we give the references for the magnetogram data. Finally, in Section 5 the results of the reconstructions are presented.

2. The approach of the reconstruction

As a starting point for the reconstruction of the solar UV irradiance we use the four-component model by Wenzler et al. (2004), Krivova et al. (2003) and the references therein, which has already been successfully applied to reconstruct the total solar irradiance (TSI) and the spectral irradiance at wavelengths longer than 300 nm. In their work they calculate synthetic solar intensity spectra with Kurucz's plane-parallel ATLAS9-code (Kurucz, 1992) for four model atmospheres: quiet Sun, faculae, umbra and penumbra. In our approach we do not distinguish between umbra and penumbra, but treat both areas with one sunspot umbra model. The practical reason for this is that we base our calculations of the synthetic intensity spectra $I_{q,s,f}(\nu)$ on the model atmospheres by Fontenla et al. (1999), and they provide only a sunspot umbra model, Model S (cf. Section 3). The time-dependent contribution of faculae and sunspot is derived from the analysis of magnetograms and represented by the filling factors a. As sunspots are bigger than the size of a pixel, a pixel falling into a sunspot is assumed to have the filling factor $a_s = 1$ (cf. Eq. (1)). In contrast, as faculae do not fill a pixel, an average field strength is measured. The filling factor a_f is assumed to linearly increase with the magnetic flux B in a magnetogram pixel to the magnetic flux saturation B_{sat}. This free parameter represents the average field strength at which the brightness of magnetic elements saturates (Wenzler et al., 2004). The time-dependent specific irradiance $S(\nu,t)$ at 1 AU is then calculated as

$$\begin{aligned} S(\nu,t) = \frac{1}{N(t)}\frac{\pi R_\odot^2}{D^2}\sum_{ip}[\{&N_{\rm tot}(\mu_{ip},t) - N_{\rm s}(\mu_{ip},t) \\ &- a_{\rm f}(\mu_{ip},B)\cdot N_{\rm f}(\mu_{ip},B,t)\}\cdot\mu_{ip}\cdot I_{\rm q}(ip,\nu) \\ &+ a_{\rm s}\cdot N_{\rm s}(\mu_{ip},t)\cdot\mu_{ip}\cdot I_{\rm s}(ip,\nu) \\ &+ a_{\rm f}(\mu_{ip},B)\cdot N_{\rm f}(\mu_{ip},B,t)\cdot\mu_{ip}\cdot I_{\rm f}(ip,\nu)], \end{aligned} \tag{1}$$

where $R_\odot$ is the solar radius, D = 1 AU is the mean distance from the Earth to the Sun, ip refers to the impact parameter in the spherical symmetric setup of the code COSI (cf. Section 3) and $\mu_{ip} = \cos(\theta_{ip})$, where θ_{ip} is the heliocentric angle at the impact parameter ip. $N(t)$ is the total number of pixels of the magnetogram at time t. $N_{tot}(\mu_{ip},t)$ is the total number of pixels in a ring found at the radial distance from the solar center corresponding to μ_{ip}, and $N_f(\mu_{ip},t)$ and $N_s(\mu_{ip},t)$ are the number of faculae pixels or sunspot pixels, respectively, in that ring. We sum over all ip from the center of the solar disk to the limb. The only free parameter in the reconstruction is the magnetic flux saturation B_{sat} of the magnetogram pixels. This parameter represents the average field strength at which the brightness of magnetic elements saturates. It has been set by Krivova et al. (2003) for the SoHO/MDI magnetograms and by Wenzler et al. (2004, 2005a,b) for the KPVT magnetograms for their reconstruction to give the best correlation with the TSI composite (version 25) compiled by Fröhlich and Lean (2004) (cf. Section 4). We adopt this value for our UV reconstruction as given by the references and keep it constant for each magnetogram data set.

3. The code COSI

COSI is a combination of a model atmosphere code in spherical symmetry, developed by Hamann and Schmutz (1987) and Schmutz (1997), and the spectrum synthesis program SYNSPEC, going back to Hubeny (1981) and further developed by Hubeny and Lanz (1992). The model atmosphere code calculates the non-LTE populations by solving the radiative transport equations simultaneously with the equations for statistical equilibrium. The radiative transfer is solved in spherical symmetry, meaning along rays (impact parameters ip) that are parallel to the central ray incident on a spherical distribution of the physical parameters (Mihalas, 1978). In contrast to plane-parallel models, where the rays are radial, this geometry allows a more realistic calculation of the emerging intensity at the limb and, in principle (not used in the present paper), allows to calculate line of sights beyond the solar limb (cf. Haberreiter et al., 2002). The calculation of an active region in spherical geometry implies that the physical parameters that represent the active region are along the full line of sight of the impact parameter *ip*.

For the non-LTE calculation we consider negative hydrogen, the first 10 levels of neutral hydrogen, ionized hydrogen, the ground states of neutral and ionized helium, as well as a few lower states of neutral carbon, aluminium, magnesium, silicon and iron as explicit non-LTE levels. The levels are selected according to their importance for the UV continuum opacity. For a complete list of the metal levels treated in non-LTE see Haberreiter and Schmutz (2003). All other transitions of metals are treated in LTE. However, it is important to include the line blanketing effect of all the line transitions in the non-LTE calculation of the level population numbers. We apply opacity distribution functions (ODFs) to account for all line opacities in the wavelength range under investigation. The ODFs are iteratively re-evaluated until they are self-consistent with the non-LTE populations. In the calculation of the synthetic spectrum the lines that are not treated in non-LTE are assumed to be in LTE.

The photoionization cross-sections for the explicit levels of carbon, aluminum, magnesium, silicon and iron are taken from the Opacity Project (Seaton et al., 1994) and the ones for iron go back to Bautista and Pradhan (1997). As theoretical ionization energies are slightly off from the observed ones, we corrected the theoretical values to agree with the measured energies. The observed ionization energies are taken from the National Institute of Standard and Technology (NIST) Atomic Spectra Database. We linearly interpolate the complex photoionization cross-sections to a coarser frequency grid. This reduces the computing time to a great extent. For further details on the implementation of the photoionization cross-sections see Haberreiter et al. (2003). The line opacities are taken from Hubeny et al. (2003).

COSI accepts atmosphere structures as an input for the calculation of synthetic spectra. We apply the empirical structures of the solar atmosphere derived by Fontenla et al. (1999) to calculate the non-LTE population numbers. In particular, we use the models for average supergranule cell interior (Model C), plage (Model P), and sunspot umbra (Model S). Finally the solar synthetic spectra are calculated with a resolution of up to 1 mÅ. In Fig. 1 we show the resulting synthetic spectrum from Model C compared with the spectrum of the quiet Sun calculated with Kurucz's ATLAS9 in LTE. The difference below 200 nm between Kurucz's spectrum and the calculation with COSI reflects mostly the importance of including the rising temperature structure of the chromosphere and transition region into the atmosphere structure. Furthermore, a correct UV spectrum can only be calculated with the treatment of the radiative transfer in non-LTE.

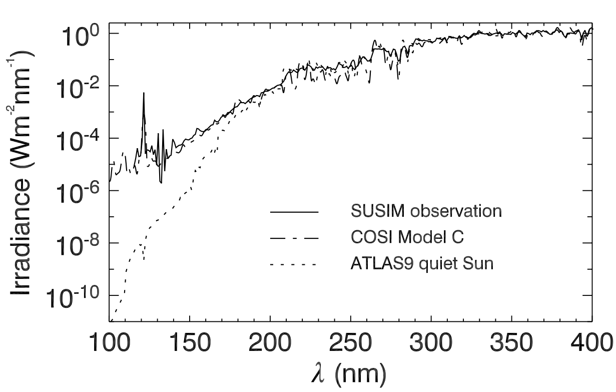

Fig. 1. Comparison of the synthetic spectrum calculated with COSI for Model C (dashed-dotted line) with the calculation with Kurucz's ATLAS9 code (dotted line) and SUSIM observation at solar minimum on April 3, 1997 (solid line).

4. The magnetogram data

Our reconstruction of the solar UV irradiance is based on the analysis of two sets of magnetograms. First, there is the record of the Solar Oscillations Investigation/Michelson Doppler Imager (SOI/MDI) on board the ESA–NASA satellite Solar and Heliospheric Observatory (SoHO), providing full-disk magnetograms since 1996. We use the analysis of the SoHO/MDI magnetograms from May 19, 1996 to April 17, 2002 carried out by Krivova et al. (2003). Second, the Kitt Peak Vacuum Tower (KPVT) of the National Solar Observatory (NSO) provided full-disk magnetograms with a lower spatial resolution from August 24, 1974 to April 7, 1992. Its analysis has been carried out by Wenzler et al. (2005b). After the Spectromagnetograph (SPM) was installed in 1992 the spatial resolution of the magnetograms became comparable to SoHO/MDI. The comparison of the SoHO/MDI and the KPVT/SPM magnetograms and the analysis of the KPVT/SPM magnetograms from January 1, 1996 to December 22, 2001 was carried out by Wenzler et al. (2004, 2005a). For the times when KPVT/SPM and SoHO/MDI magnetograms are available, we used the SoHO/MDI data set, as the space-born magnetograms do not show any effects caused by the Earth's atmosphere (e.g., clouds).

5. Reconstruction back to 1975

We reconstructed the spectral solar UV irradiance for the wavelength range from 1150 to 4000 Å on a daily basis. In Fig. 2 on the left panel the reconstruction for H I λ1216, integrated from 1210 to 1220 Å, is compared with the Lyman α composite compiled by Woods et al. (2000) and on the left panel it is compared with the SUSIM V21 data (Floyd et al., 2002; Brueckner et al., 1993). Our reconstruction underestimates the variability

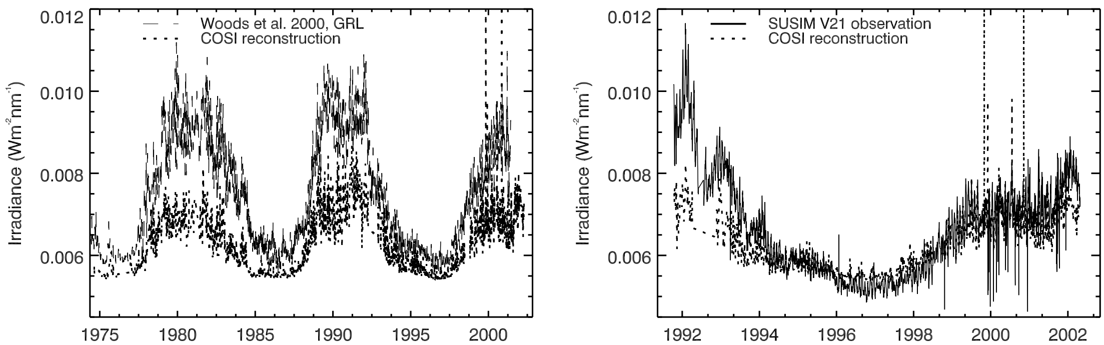

Fig. 2. Comparison of our reconstruction of Lyman α (dotted line) with the composite by Woods et al. (2000) (dashed line, left panel) and its comparison with the SUSIM V21 observation (solid line, right panel).

of the Lyman α composite for the whole time series (left panel), whereas it reproduces the SUSIM V21 data for the time between 1994 and 2002 very well (right panel). However, before 1994 our reconstruction also underestimates the SUSIM observation. Interestingly, the minimum of the SUSIM V21 data around 1997 matches well with our reconstruction, whereas the minimum of the Lyman α composite is slightly higher than the one of our reconstruction. The fact that COSI reproduces the SUSIM Data from 1994 to 2002 very well shows that the COSI reconstruction of the quiet Sun is within the uncertainty of the observations. However, the fact that we underestimate the maximum around 1992 for both data sets indicates that the temperature structures used here to represent the active regions (Model P, S) need further improvements.

In Fig. 3, the relative variability $(S_{\max,\lambda} - S_{\min,\lambda})/S_{\min,\lambda}$ of the irradiance over the solar cycle at each 1-nm bin is compared with the relative variability of the daily (dotted line) and the 7-day running mean of the SUSIM V21 data. As the shortterm variability of the timescale of days is not taken into account in our reconstruction, we discuss our results in relation to the relative variability of the 7-day mean of the SUSIM observations. From 115 to 280 nm the relative variability of the reconstruction presented here is lower than the relative variability of the observation, but longward of 280 nm the relative variability of our reconstruction matches the relative variability of the 7-day mean of the SUSIM observation very well. This indicates that the underlying process of the UV-variability is well described by our approach.

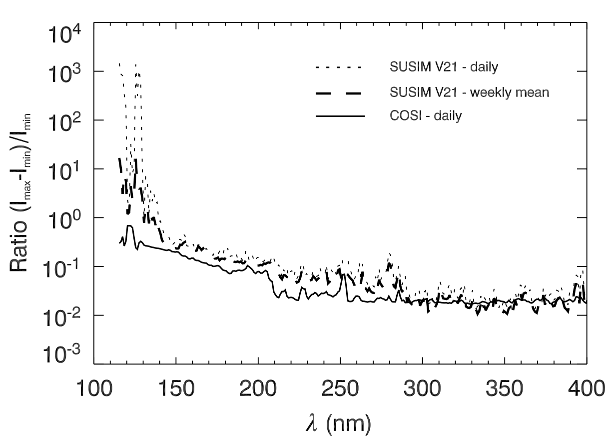

Fig. 3. Comparison of the relative variability of the UV reconstruction (solid line) with the relative variability of the daily (dotted line) and the 7-day mean (dashed line) of the SUSIM V21 observation.

6. Conclusion

We present reconstructions of the solar UV irradiance on a daily basis back to 1974. The reconstructions are based on non-LTE radiative transfer calculations with the code COSI and the analysis of ground-based and space-based magnetograms. The comparison of the SUSIM observations with the composite by Woods et al. (2000) shows that our reconstruction underestimates the variability of the solar UV irradiance. A reason could be that the temperature structure representing an average faculae Model P is not sufficiently hot. Another reason could be that the magnetic saturation flux, which has been set to reconstruct the TSI, is not appropriate for the UV reconstruction. As we present work in progress, these issues will be addressed in the near future.

Acknowledgment

The work was supported under the Polyproject No. 9947 *Variability of the Sun and Global Climate* of the ETH Zürich, Switzerland.

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