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Advances in Space Research 35 (2005) 361–364

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
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Reconstruction of solar UV irradiance

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Received 8 September 2004; received in revised form 8 December 2004; accepted 9 December 2004

Abstract

Understanding solar influence on the Earth's climate requires a reconstruction of solar irradiance for the pre-satellite period. Considerable advances have been made in modelling the irradiance variations at wavelengths longer than 200 nm. At shorter wavelengths, however, the LTE approximation usually taken in such models fails, which makes a reconstruction of the solar UV irradiance a rather intricate problem. We choose an alternative approach and use the observed SUSIM UV spectra to extrapolate available models to shorter wavelengths.

Keywords: Solar activity; Solar irradiance; Solar-terrestrial relations; Solar UV radiation

1. Introduction

Solar variability on time scales of days to centuries has commanded considerable attention since it is likely to impact the Earth's climate. Among the possible causes of this influence are variations in solar total and spectral (in particular, UV) irradiance, leading to changes in the energy input to the Earth's atmosphere or in stratospheric chemistry, respectively. The record of regular measurements of solar total irradiance starts in 1978 and that of the UV irradiance is even shorter. Reconstructions of total and spectral irradiance at earlier times are, therefore, needed in order to allow their comparison with climate records.

A notable advance has been made in modelling the irradiance variations at wavelengths larger than 200 nm on both short (up to the solar cycle) and long (over decades and centuries) time scales (e.g., Solanki and Fligge, 1999; Fligge and Solanki, 2000; Krivova et al., 2003; Krivova and Solanki, 2003; Wenzler et al., 2004a). In contrast, models at shorter wavelengths leave much to be desired (see e.g., the review by Woods, 2002).

The successful models of the total and spectral (longward of ≈200 nm) irradiance involve LTE calculations of the brightness of different photospheric components (e.g., Fontenla et al., 1999; Unruh et al., 1999). The LTE approximation, however, fails at shorter wavelengths which is demonstrated by Fig. 1. This figure shows two solar spectra between 115 and 410 nm, one representing the UARS SUSIM (Brueckner et al., 1993) measurements, the other the model following Krivova et al. (2003). Using a non-LTE approximation is one obvious line of attack on the problem (e.g., Haberreiter et al., 2005). We take an alternative approach and use observed UV spectra to extrapolate available models to shorter wavelengths. These semi-empirical models are then used to reconstruct solar UV irradiance at earlier times.

2. Approach

As the initial model we take the one by Krivova et al. (2003). It assumes that the irradiance variations on time

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0273-1177/$30
doi:10.1016/j.asr.2004.12.027

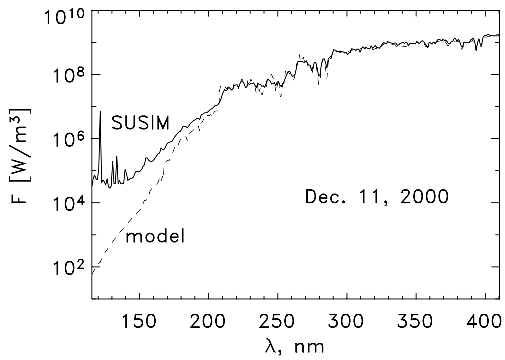

Fig. 1. UV irradiance of the Sun on 11.12.2000: observed (solid curve) by UARS SUSIM (Brueckner et al., 1993) and modelled (dashed) following Krivova et al. (2003).

scales of days to the solar cycle are caused by the solar surface magnetic field and allows both the total and spectral irradiance to be calculated using model atmospheres under the assumption of LTE (Unruh et al., 1999). The model reproduces more than 90% of all total irradiance changes in cycle 23 and also agrees with measurements by the three VIRGO (on SoHO; Fröhlich et al., 1997) spectral channels: blue, green and red centred at 402, 500 and 862 nm, respectively. It has also been successfully extended by Wenzler et al. (2004b) to cycle 22.

The model is extrapolated to shorter wavelengths using UARS SUSIM data. UARS was launched in 1991 carrying, among others, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM; Brueckner et al., 1993). SUSIM has been measuring the solar spectral UV irradiance between 115 and 410 nm. We use daily level 3BS data from ftp://susim.nrl.navy.mil.

In a first step, we have compared SUSIM spectra with the model in different spectral intervals and their change with solar activity between 1996 and 2002. For this, 70 days (typically one per month) have been extracted when both the SUSIM data and the model (i.e., MDI data, see Krivova et al., 2003) were available. A good agreement has been found at, e.g., 220–240 or 240–260 nm. We choose the first range as reference because longward of 250 nm the long term accuracy of SUSIM becomes comparable to the cyclic variation of the solar irradiance (e.g., Woods et al., 1996; DeLand et al., 2004). The solar integral irradiance in the range 220–240 nm as a function of time between 1996 and 2002 is plotted in Fig. 2. Both the model and the SUSIM data are shown.

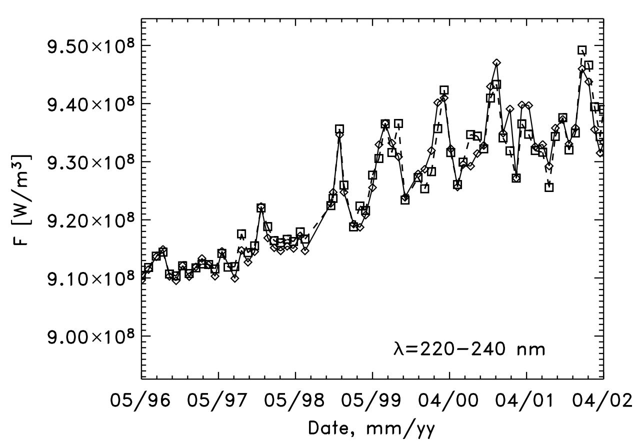

Fig. 2. The solar irradiance integrated over the wavelength range 220–240 nm as a function of time for 70 days during 1996–2002. Diamonds connected by the solid line represent SUSIM measurements and squares connected by the dashed line the model by Krivova et al. (2003).

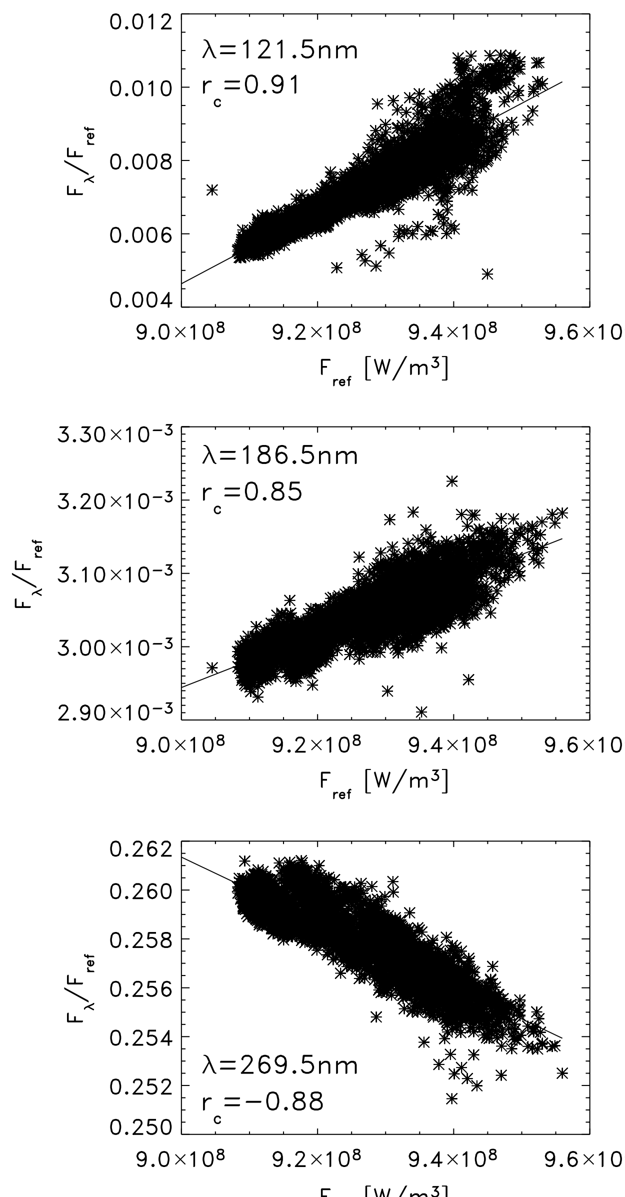

Fig. 3. Ratio $F_\lambda/F_{\rm ref}$ as a function of $F_{\rm ref}$ (where 'ref' refers to the reference interval 220–240 nm) at three wavelengths (from top to bottom): 121.5, 186.5 and 269.5 nm. The asterisks denote SUSIM measurements and the solid lines represent regressions to these data. The corresponding correlation coefficients, r_c, are also given.

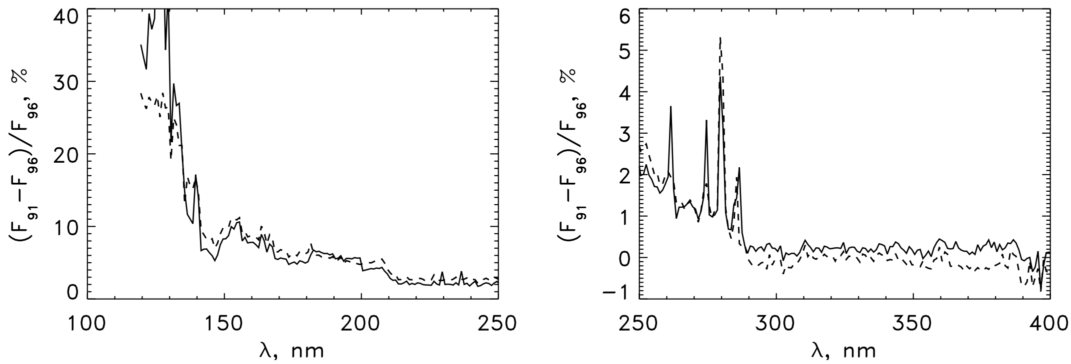

Fig. 4. Relative irradiance variations between the solar spectrum in 1991 (soon after the activity maximum in 1989) and at activity minimum in 1996 at 100–250 nm (left) and 250–400 nm (right). The solid line represents SUSIM measurements and the dashed line our reconstruction.

In the next step, we find relations between irradiances, F_λ, at a given wavelength, λ, and in the reference interval, F_{ref} (220–240 nm). This is done for every λ on the basis of daily SUSIM data. Examples of such regressions, F_λ/F_{ref} vs. F_{ref}, are presented in Fig. 3. The corresponding correlation coefficients are also indicated.

Finally, solar UV irradiance at 115–300 nm is reconstructed back to the end of the Maunder minimum. For this, the irradiance in the reference range, 220–240 nm, is calculated using the model by Fligge and Solanki (2000) and then extended to other wavelengths with the help of the F_λ/F_{ref} vs. F_{ref} relationships.

3. First results

Initial results of the model described above are presented in Figs. 4 and 5. We first look at the results in the period when SUSIM measurements are available in order to validate our reconstruction. For this we choose two periods, each two months long. The first is right after the launch of UARS in 1991 (i.e., relatively soon after the official activity maximum in 1989), the other lies at activity minimum in 1996. The relative irradiance variations, $(F_{91} - F_{96})/F_{96}$, both measured and modelled, are shown in Fig. 4. At wavelengths longer than ~130 nm both agree quite well with each other. Note that longward of 300 nm the measurement uncertainty is higher than the amplitude of the long-term irradiance variation (Woods et al., 1996; DeLand et al., 2004). At wavelengths shorter than ~130 nm the model underestimates the cyclic variation and needs to be improved. Floyd et al. (1997) compared the short- and long-term behaviour of the Ly-α index and the 200–205 nm irradiance with that of the Mg II index. They found that the magnitude of the 27 day periodicity in Ly-α was smaller relative to the solar cycle change than for the other two values. Therefore a multiple regression was needed to fit both the short- and long-term variations. In Fig. 3 (top) we observe a similar behaviour for Ly-α. This might be the reason why we underestimate the cyclic change at shorter wavelengths. Nevertheless, the difference between the observed and modelled relative irradiance variations lies at all wavelengths within the 2σ uncertainty of the SUSIM data (Brueckner et al., 1993).

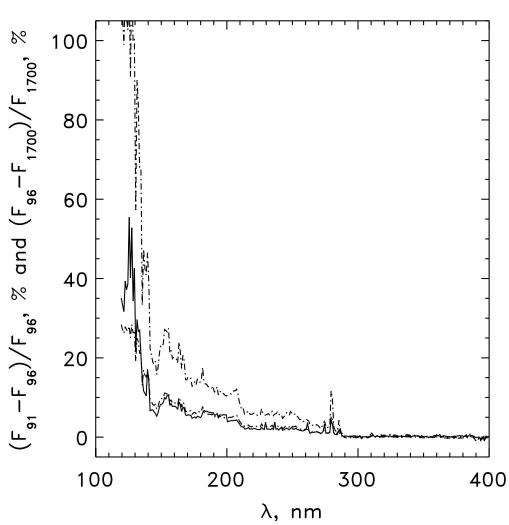

Fig. 5. The same as Fig. 4 but now also showing the model estimate for the relative difference between the flux during the last activity minimum and the Maunder minimum (dot-dashed line).

In Fig. 5 we also show a very preliminary prediction for the Maunder minimum, i.e., for the 'very' quiet Sun (dot-dashed curve). The integral 220–240 nm irradiance for this curve was obtained using the cycle-length based model for the long term change (see Fligge and Solanki, 2000) and assuming a 4 W m^{-2} increase in the total irradiance since the Maunder minimum. The magnitude of this secular change is a matter of intense debate and the value we used is near the top end of values proposed in the literature (e.g., the recent work by Foster and Lockwood, 2004 suggests a value of 1.7 W m^{-2}). Therefore these very preliminary computations represent rather an upper limit for the UV irradiance change since the Maunder minimum. The computations suggest that the irradiance at that time could have been up to 5–30%

lower at $\lambda \approx 150$–300 nm and even up to a factor 2 at shorter wavelengths, as compared to recent activity minima.

4. Conclusions

Using SUSIM measurements of solar UV irradiance, we have extended our short (Krivova et al., 2003) and long-term (Fligge and Solanki, 2000) models of total and spectral irradiance to shorter wavelengths ($\approx$115–220 nm). The model reproduces observed solar cycle variations of the irradiance at wavelengths longer than $\approx$130 nm, but somewhat underestimates variations in the range $\lambda \approx 115$–130 nm. Although the difference with the measurements is within the 2σ uncertainty of SUSIM at all wavelengths, further improvement is needed and possible. On longer time scales, we estimate that the irradiance during the Maunder minimum was up to a factor of 2 lower at and around Ly-α and up to 5–30% lower at $\lambda \approx 150$–300 nm.

Acknowledgement

We thank L. Floyd for valuable comments on SUSIM data.

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