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Reconstruction of solar irradiance variations in cycle 23: Is solar surface magnetism the cause?

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Abstract. A model of solar irradiance variations is presented which is based on the assumption that solar surface magnetism is responsible for all total irradiance changes on time scales of days to years. A time series of daily magnetograms and empirical models of the thermal structure of magnetic features (sunspots, faculae) are combined to reconstruct total (and spectral) irradiance from 1996 to 2002. Comparisons with observational data reveal an excellent correspondence, although the model only contains a single free parameter. This provides strong support for the hypothesis that solar irradiance variations are caused by changes in the amount and distribution of magnetic flux at the solar surface.

Key words. solar-terrestrial relations – Sun: activity – Sun: faculae – Sun: magnetic fields – sunspots

1. Introduction

Regular space-borne measurements of solar irradiance since 1978 show that it varies on all accessible time scales (Willson & Hudson 1988, 1991; Fröhlich 1994; Fröhlich & Lean 1998). The physical cause of these variations, however, remains a subject of debate. Most successful were models assuming that the variations of the total solar irradiance are essentially caused by the evolution of the solar surface magnetic field (Foukal 1992; Chapman et al. 1996; Fligge et al. 1998, 2000a,b). However, it has been argued, that solar irradiance variations in cycle 23 could not be interpreted in terms of surface magnetic features alone, implying another or additional mechanism of irradiance change (de Toma et al. 2001). There is thus a strong need for detailed and extensive modelling in order to identify the main mechanism responsible for solar irradiance variations. Also, understanding and successful modelling of irradiance variations are important for a reconstruction of the irradiance for the pre-satellite period.

In this paper we present a model (Sect. 2) of solar irradiance variations based on the evolution of the solar surface magnetic field and show that this model reproduces solar total (Sect. 3.1) and spectral (Sect. 3.2) irradiance changes on time-scales from days to years, covering the rising and maximum phases of cycle 23. Our results are summarized in Sect. 4. A preliminary, partial reconstruction was published by Fligge et al. (2000a). The reconstruction presented here covers solar cycle 23 far more completely, is based on an updated MDI data-set and is compared with the newest level 2 VIRGO data.

2. Model

Our model (see also Fligge et al. 1998, 2000a,b) is based on the assumption that the irradiance change is entirely determined by the evolving magnetic field at the solar surface. We adopt a four-component model for the solar photosphere: quiet Sun (subscript q in the subsequent discussion), sunspots, with umbra (u) and penumbra (p) being treated separately, and faculae (f). For a complete description of the irradiance change with time, t, we need the intensity of each component, $I(\mu,\lambda)_{\mathrm{q,u,p,f}}$, which depends on the wavelength λ and the heliocentric angle, θ ($\mu = \cos\theta$), and the fraction of the solar surface that is covered by this component, filling factors, $\alpha(i,j;t)_{\mathrm{q,u,p,f}}$. Here (i,j) number the points of a rectangular grid (pixels) covering the solar disc. The irradiance is then calculated in the following

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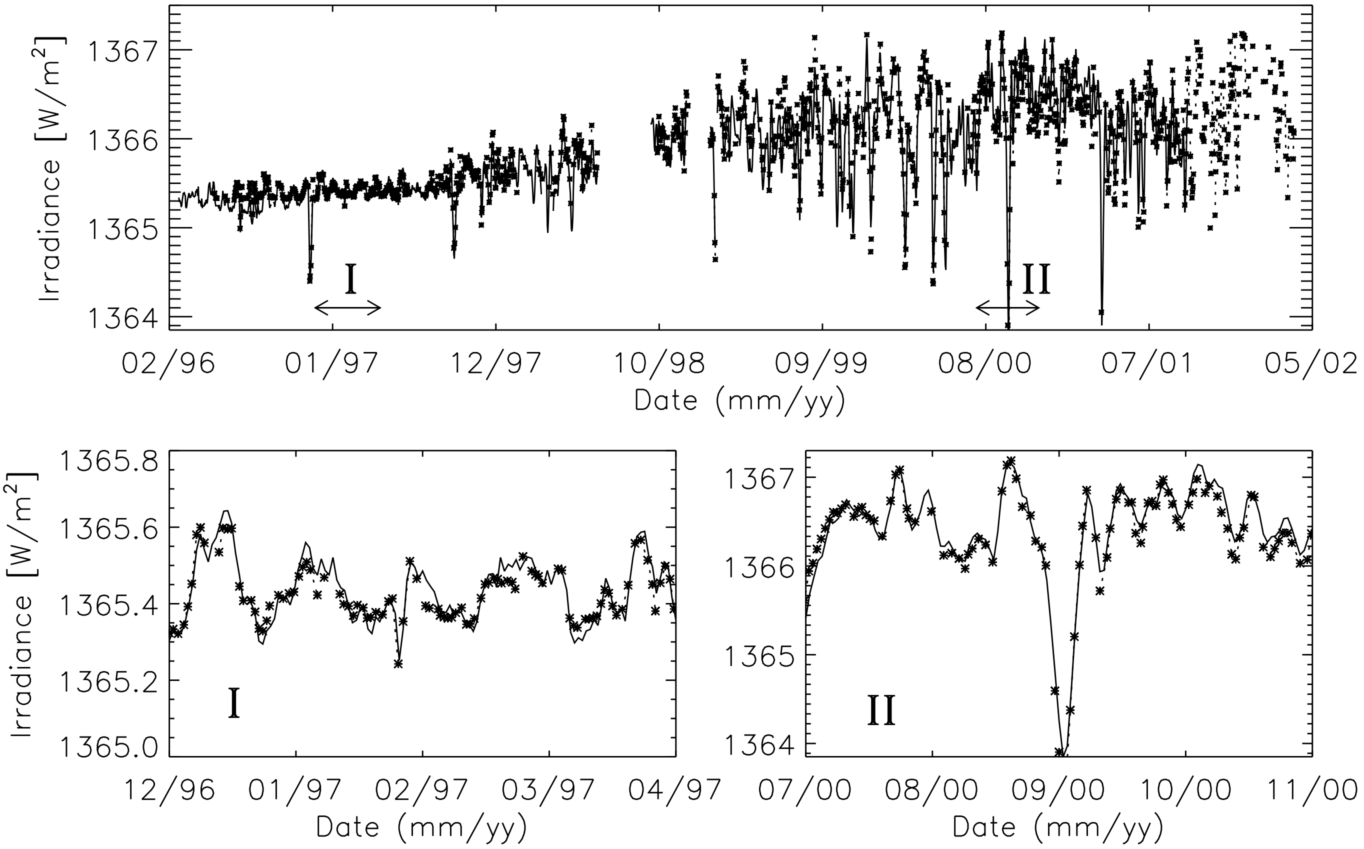

Fig. 1. Reconstruction (asterisks connected by dotted curve when there are no data gaps) of total solar irradiance for about 1500 individual days between 1996 and 2002, i.e. from the minimum of cycle 23 to its maximum (top panel). The irradiance record measured by VIRGO is represented by the solid line. The bottom panels show a zoom-in to two shorter intervals at different activity levels. The times corresponding to these zoom-ins are marked in the top panel by roman numerals.

manner:

$$\begin{aligned}F(\lambda,t) = & \sum_{i,j}\Big[\alpha_{\mathrm{u}}(i,j;t)I_{\mathrm{u}}(i,j;\lambda)+\alpha_{\mathrm{p}}(i,j;t)I_{\mathrm{p}}(i,j;\lambda)\\ & +\alpha_{\mathrm{f}}(i,j;t)I_{\mathrm{f}}(i,j;\lambda)+(1-\alpha_{\mathrm{u}}(i,j;t)-\alpha_{\mathrm{p}}(i,j;t)\\ & -\alpha_{\mathrm{f}}(i,j;t))I_q(i,j;\lambda)\Big]. \qquad (1)\end{aligned}$$

The intensities $I(i,j;\lambda)_{\mathrm{q,u,p,f}}$ are calculated using the ATLAS9 code of Kurucz (1992) from plane-parallel model atmospheres of the quiet Sun, umbra, penumbra and faculae. The I values depend on (i,j) through their dependence on μ. We use the standard model atmosphere FAL-C (Fontenla et al. 1993) for the quiet Sun and an appropriate radiative equilibrium model for the sunspots (Kurucz 1991; Severino et al. 1994; Solanki 1997). The umbra and penumbra are represented by model atmospheres with $T_{\mathrm{eff}} = 4500$ K and $T_{\mathrm{eff}} = 5400$ K, respectively. For the faculae we have used a slightly modified version of FAL-P (Fontenla et al. 1993). Detailed information on the facular model is given by Unruh et al. (1999). Note that it is a plane parallel model that does not take into account the unresolved fine structure (magnetic elements).

The filling factors $\alpha(i,j;t)_{\mathrm{q,u,p,f}}$ are extracted from daily full-disc magnetograms and continuum images recorded by the Michelson Doppler Interferometer (MDI, Scherrer et al. 1995) on board the SOHO spacecraft. From the continuum images we identify pixels belonging to umbra and penumbra and having $\alpha_{\mathrm{u}} = 1$ or $\alpha_{\mathrm{p}} = 1$, respectively. The magnetograms are used to determine α_{f}. Pixels with a magnetogram signal above three times the noise level, which do not lie within sunspots are counted to faculae. Since noise in the magnetograms is position dependent, we use a 2-D representation of it following Ortiz et al. (2002). To decrease the noise level we employ 5-minute averages over consecutive 1-minute magnetograms (final average noise level of about 9 G). Since only a single facular atmosphere is used, while the brightness of faculae and the network depends on the amount of magnetic flux per area (Frazier 1971; Topka et al. 1997; Ortiz et al. 2002), we need to scale I_{f} by this quantity for every pixel. The scaling factor $\alpha_{\mathrm{f}}(i,j)$ is chosen to linearly depend on $\Phi_{i,j} = M_{i,j}/\mu$, where $M_{i,j}$ is the magnetogram signal measured in the pixel (i,j) and μ takes into account that a longitudinal magnetogram underestimates the true flux in pixels closer to the limb since fields on the Sun are mainly vertically oriented. There is strong evidence, however, that the magnetic elements in regions with higher flux are less bright (e.g., Solanki 1986; Solanki & Brigljević 1992) while their filling factor keeps increasing, so that the brightness of faculae saturates to first order (e.g., Foukal & Fowler 1984; Ortiz et al. 2002). We take this into

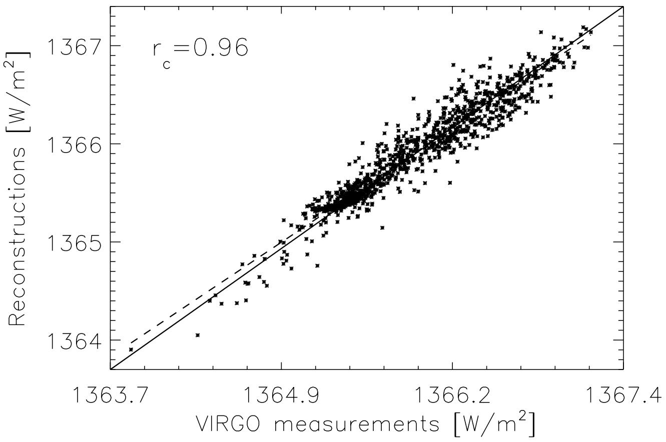

Fig. 2. Modelled total solar irradiance vs. measured (the correlation coefficient $r_c = 0.96$). The solid diagonal line represents the expectation values for a perfect model fit, the dashed line is a regression.

account in a simple manner by introducing a parameter, $\Phi_{\rm sat}$. The proportionality factor between $M_{i,j}/\mu$ and $\alpha(i, j)$ is chosen such that $\alpha_{\rm f}(i, j) = 1$ for $\Phi_{i,j} = \Phi_{\rm sat}$. For $\Phi_{i,j} > \Phi_{\rm sat}$ we keep $\alpha_{\rm f} = 1$ to describe this saturation (i.e. all faculae with larger magnetic flux per pixel are equally bright). The value of $\Phi_{\rm sat}$ is the only free parameter in our model, which reflects the uncertainty in the relation between facular brightness (or contrast) and magnetogram signal. $\Phi_{\rm sat}$ is determined by requiring that the model should reproduce the observed irradiance variations and corresponds to faculae. Note, that it is fixed for the whole period of reconstructions and in particular this single free parameter must reproduce both short-term variations in irradiance caused by solar active regions passing across the solar disc as the Sun rotates and the slow variation over the solar cycle.

3. Results

3.1. Total irradiance

The output of the model for the period between May 1996 and April 2002 is plotted in the top panel of Fig. 1 (asterisks connected by dotted curve). Also plotted (solid curve) are the VIRGO (Variability of solar Irradiance and Gravity Oscillations; Fröhlich et al. 1995) total irradiance measurements between January 1996 and September 2001 (level 2; Fröhlich & Finsterle 2001). The two lower panels display extracts on an enlarged scale at different phases of the solar cycle. Two further such extracts are shown at the top of Fig. 3. Both, short-term variations and the minimum-to-maximum increase of the total irradiance are very well reproduced. The excellent correspondence between the data and the model and the absence of any significant bias in the latter is also evident from Fig. 2, where the reconstructed value is plotted against the measured irradiance (the correlation coefficient $r_c = 0.96$).

3.2. Spectral irradiance

The model has also been used to calculate spectral irradiance variations. Note, that the value of $\Phi_{\rm sat}$ was the same as for the total irradiance. Here we compare our model with the measurements in the three VIRGO colour channels: red, green and blue centred at 862 nm, 500 nm and 402 nm, respectively. Unfortunately, the sensitivity of VIRGO's spectral photometers is not stable enough to allow a comparison of the reconstructed and measured spectral irradiance records over the full period and it is impossible to remove the long-term instrumental trends completely. Therefore, in Fig. 3 we give two 4-month long extracts of the measured and modelled irradiance in each channel. Left panels represent a relatively quiet period (1997), the right panels a period near activity maximum (2000). The corresponding total irradiance record is also shown (top panels). The modelled irradiance values are connected by dotted lines whenever no gap is present (gaps may be caused, e.g., by lack of suitable 5-min averaged magnetograms).

The calculated values in the green and blue channels show somewhat higher scatter than in the case of the total and red irradiance, but nevertheless the agreement is good for all the channels. Also, it is not clear, which fraction of the difference between data and model is due to residual trends in the photometer records. This implies that the simple model we use is essentially correct. On a longer time-scale, from the onset of cycle 23 to its maximum, the increase in the blue channel is predicted by the model to be about twice as large as in the total irradiance and the red channel.

4. Conclusions

We have reconstructed solar total and spectral irradiance from the onset of solar cycle 23 to its maximum. Our model is based on the assumption that solar irradiance changes are entirely caused by the evolution of the solar surface magnetic field. We represent the solar photosphere by four components describing the quiet Sun, sunspot umbrae, sunspot penumbrae and faculae. The distribution of magnetic features over the solar disc at each instant of time is extracted from SOHO MDI 5-minute magnetograms and intensity images.

We have compared the reconstruction with VIRGO measurements. The calculated total irradiance shows excellent agreement with observations on both short (days to months) and long (solar cycle) time-scales. In particular, no additional component is necessary to reproduce the long-term increase of solar irradiance between activity minimum and maximum apart from sunspots and small magnetic features forming faculae and the network. The modelled spectral irradiance variations are also consistent with VIRGO colour observations, although a long-term comparison is not possible due to the degradation of the VIRGO spectral photometers.

The excellent correspondence between model and data supports the conclusion that the magnetic field at the solar surface is the main driver of the solar irradiance variability at time scales of the solar rotation and the solar cycle. In a future paper, we plan to further relax the assumptions described in Sect. 2 and to remove the single free parameter of the model.

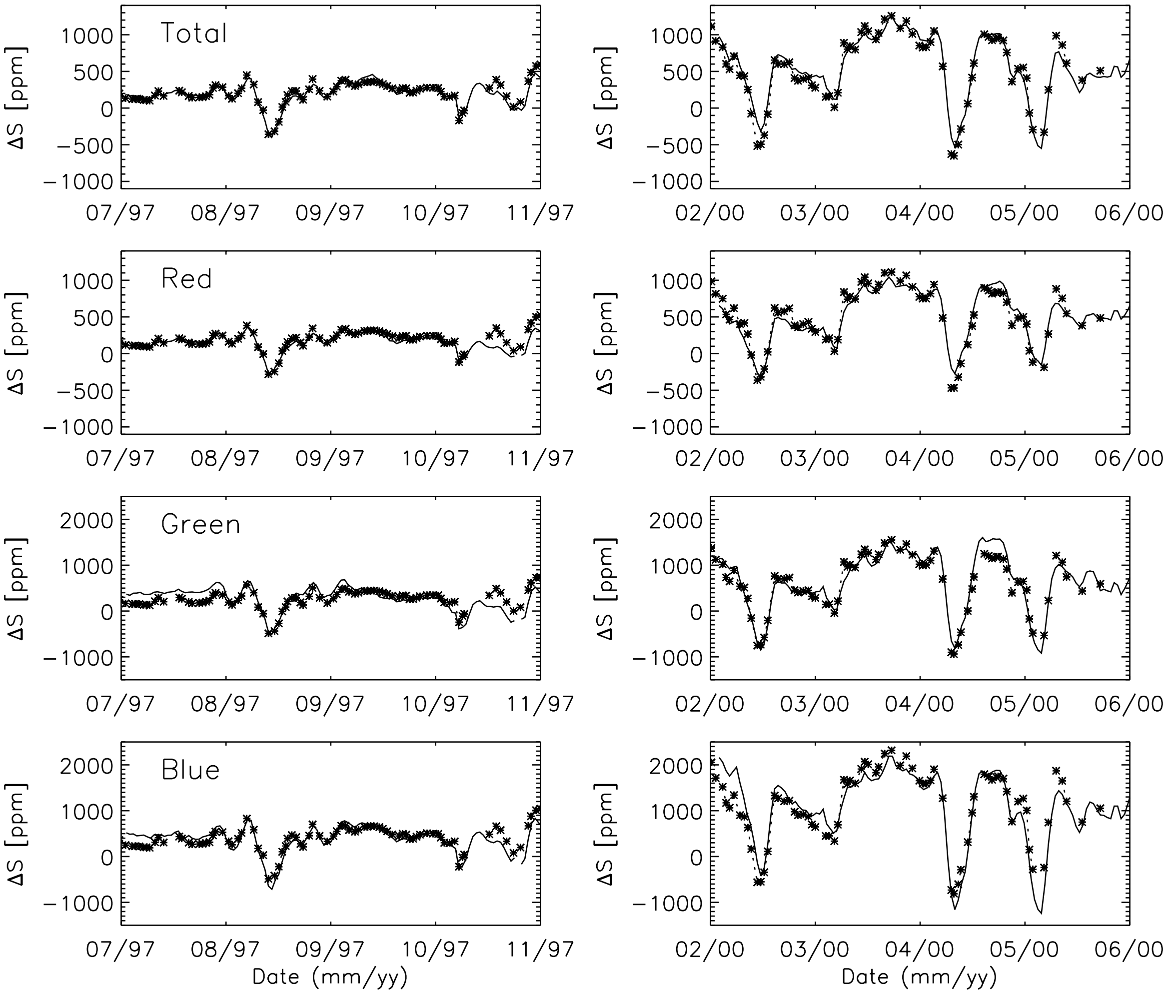

Fig. 3. From top to bottom: reconstructed irradiance variations (asterisks connected by dotted lines) for the total solar irradiance as well as for the three VIRGO spectral channels centred at 862 nm, 500 nm and 402 nm for two periods of 4 months each around activity minimum (left panels) and maximum (right panels). The VIRGO measurements are represented by the solid line.

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