SOLAR SURFACE MAGNETISM AND THE INCREASE OF SOLAR IRRADIANCE BETWEEN ACTIVITY MINIMUM AND MAXIMUM

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ABSTRACT

We present model reconstructions of solar total and spectral irradiance variations based on the assumption that solar irradiance changes are entirely produced by solar surface magnetic features.

The model makes use of calculations of sunspot and facular contrasts as a function of wavelength and limb angle. The distribution of magnetic features on the solar surface is extracted from averaged MDI magnetograms.

We reconstruct the irradiance measured by VIRGO between 1996 and 2000, i.e. from the onset of solar cycle 23 right into its maximum. Preliminary results show that the model is able to reconstruct both short-term (days to weeks) and long-term (years) solar irradiance variations simultaneously. No further component of non- or only indirectly magnetic origin is necessary to explain the observed irradiance changes.

Key words: Solar Irradiance; Faculae; Sunspots; Active Network.

1. INTRODUCTION

Solar irradiance variations are closely related to the evolution of the magnetic field at the solar surface (Foukal & Lean, 1988; Lean et al., 1998; Fligge et al., 2000; Fligge & Solanki, 2001). The appearance and evolution of active regions on the solar surface leaves distinct fingerprints in modern irradiance records which can easily be measured with space-borne instruments (Hudson et al., 1982; Willson & Hudson, 1988; Fröhlich, 2000). Sunspots and active region-faculae, hence, are generally considered to be the dominant contributors to solar irradiance changes on time-scales of days to weeks (Fröhlich & Pap, 1989; Fligge et al., 1998, 2000).

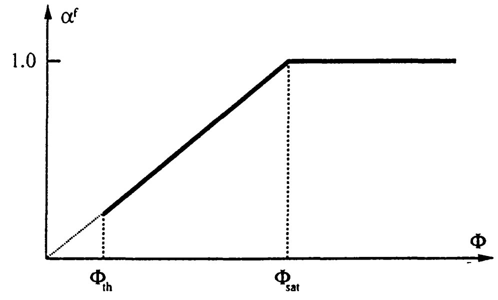

Figure 1. Relationship used to convert magnetic flux Φ measured within a pixel of a magnetogram into a corresponding facular filling factor α^f. The facular filling factor α^f increases linearly from $\Phi_{\rm th}/\Phi_{\rm sat}$ at the threshold flux, $\Phi_{\rm th}$, to 1.0 at the saturation flux, $\Phi_{\rm sat}$.

The origin of the longer-term increase of solar irradiance between activity minimum and maximum is less clear, however, and still widely debated. Small-scale magnetic elements composing the active network can be expected to contribute substantially to the observed irradiance increase during activity maximum (Foukal & Lean, 1988; Solanki & Fligge, 2001). However, other sources of non-magnetic or only indirectly magnetic origin have also be proposed, based on, e.g., the theory of r-mode oscillations (Wolff & Hickey, 1987a,b) or photometric measurements of the solar limb reported by Kuhn et al. (1988) and Kuhn & Libbrecht (1991).

In the following, we present a model of solar irradiance variations that is entirely based on temporal changes of the surface distribution of the solar magnetic field. Within a single run the model reproduces both, solar irradiance changes on time-scales of days to weeks as well as the long-term increase of solar irradiance on the solar cycle time-scale. The model has only a single free parameter to be fixed by fitting the VIRGO (Variability of IRradiance and Gravity Oscillations, Fröhlich et al., 1995). This provides further evidence that it is indeed the magnetic field at

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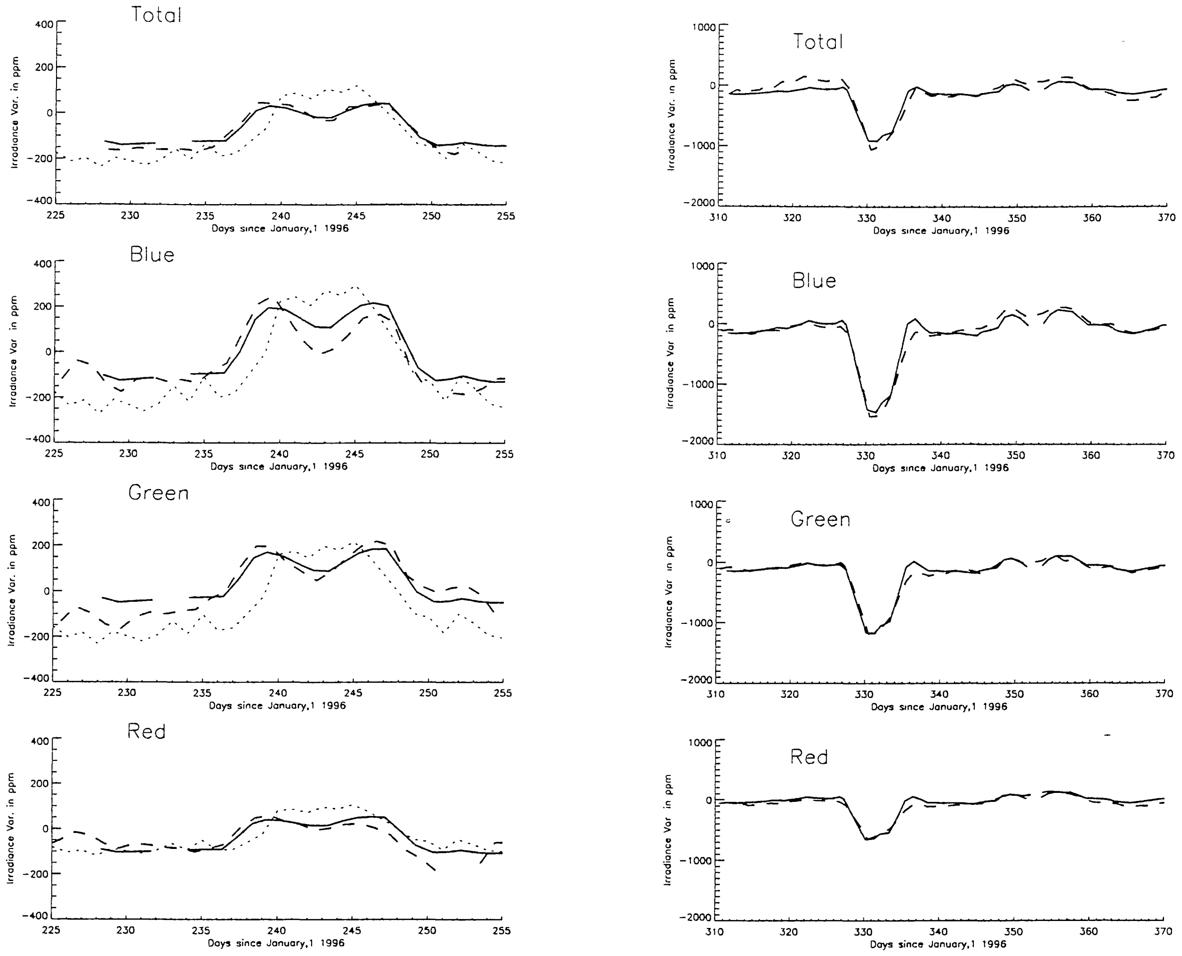

Figure 2. Comparison between measured (dashed) and modeled (solid) solar total and spectral irradiance variations for the time between 15 August and 15 September 1996 (left panel) and 6 November 1996 and 6 January 1997 (right panel), respectively. Plotted are (from top to bottom) the total irradiance, and the spectral irradiance variations measured in the blue, green and red color channels of VIRGO, respectively. Our model reproduces the double-peaked structure originating from the CLV of the facular contrast (left panel). However, some deviations from the measurements remain unexplained. For comparison, the dotted curve in the left panel shows a reconstruction which neglected the CLV of the facular contrast. The dimming of solar irradiance due to the passage of sunspots (right panel) is also well reproduced.(From Fligge et al., 2000)

the solar surface which is responsible for by far the largest fraction of the observed irradiance variations – at least on time-scales accessible by modern measurements.

2. THE IRRADIANCE MODEL

The irradiance model described below rests upon the following basic assumptions. Firstly, we assume that irradiance variations are entirely caused by the magnetic field at the solar surface. This premise implies that no additional component of non-magnetic or only indirectly magnetic origin is necessary to explain the observed irradiance changes. Secondly, it is sufficient to divide the solar surface into only the following components, i.e. quiet Sun, sunspots (for which umbral and penumbral regions are treated separately, however) and faculae. In particular, active region faculae and the active network features are described by the same model atmosphere. Finally, the atmospheric models used to calculate the intensity spectra of each individual component do not change in time. Temporal variations are exclusively due to the changing surface coverage of the Sun by the individual components.

Within the framework of this model, two basic ingredients are necessary to reconstruct solar irradiance variations. Firstly, we need a detailed description of the distribution of the magnetic field on the solar surface and its evolution in time. This can be gained from a careful analysis of a time series of full-disc magnetograms.

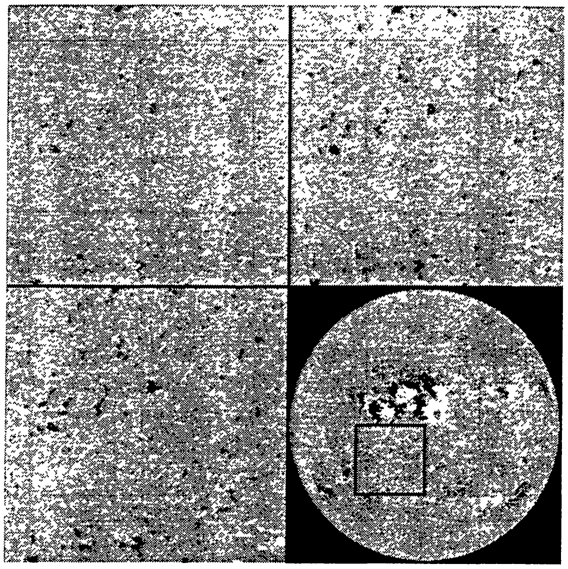

Figure 3. Extraction of the active network from MDI magnetograms averaged over 1-min (upper left), 5-min (upper right) and 20-min (lower left), respectively. The frame in the full-disc magnetogram (lower right) marks the considered network region.

Secondly, the intensity I of each individual component as a function of wavelength λ and position $\mu = \cos\theta$ (where θ is the heliocentric angle) on the solar disc must be known. These are calculated using Kurucz' spectral synthesis code ATLAS9 (Kurucz, 1992) from plane-parallel model atmospheres of the quiet Sun, sunspot umbrae, sunspot penumbrae and faculae. We use the standard model atmosphere FAL-C (Fontenla et al., 1993) for the quiet Sun and an appropriate radiative equilibrium model (Kurucz, 1991) for the sunspots (cf. Severino et al., 1994; Solanki, 1997). The umbra is represented by a model atmosphere of $T_{\rm eff} = 4500$ K while $T_{\rm eff} = 5400$ K has been chosen for the penumbra. The employed facular model is a slightly modified version of FAL-P of Fontenla et al. (1993) for which details are given by Unruh et al. (1999).

The intensity of a pixel (i, j) on the solar surface at wavelength λ and time t can then be written as a sum over the contributions from the individual components, i.e.

$$\begin{aligned} I_{i,j}(\lambda;t) &= \sum_{x=u,p,f} \alpha^{x}_{i,j}(\Phi;t) \cdot I^{x}(\mu(i,j),\lambda) \qquad (1) \\ &+ \ (1 - \sum_{x=u,p,f} \alpha^{x}_{i,j}(\Phi;t)) \cdot I^{q}(\mu(i,j),\lambda), \end{aligned}$$

where $I^{u,p,s,q}(\mu,\lambda)$ stands for the intensity spectrum of the umbral, penumbral, facular and quiet Sun component, respectively.

The filling factors $\alpha^{u,p,f,q}_{i,j}(\Phi;t)$, i.e. the fractional coverage of any pixel (i, j) by one of the components, are extracted from full-disc magnetograms by converting the measured magnetogram signal Φ into the corresponding filling factor α (where $\Phi = \phi/\mu$ and ϕ is the magnetogram signal). For sunspots (umbra and penumbra) we set $\alpha^{u}_{i,j} = \alpha^{p}_{i,j} = 1$ since they are well resolved by the used MDI full-disc magnetograms. Faculae are more loosely packed and we expect $\alpha^{f}_{i,j} < 1$ for the weaker features. The applied conversion scheme for faculae is shown in Fig. 1. Starting at $\Phi_{\rm th}$, i.e. the threshold value given by the noise level of the magnetograms, the filling factor increases linearly to $\alpha^{f} = 1$ at $\Phi_{\rm sat}$. The $\Phi_{\rm th}$, the only free parameter in our model, is determined by requiring that the model should reproduce the observed irradiance variations.

Finally, the irradiance is calculated by integrating the intensity over the whole solar disc, i.e. by summing up the contributions from the individual pixels.

3. RESULTS

3.1. Short-term variability

The model has first been used to reconstruct solar irradiance variations over a time period of, respectively, one and two month during activity minimum when the influence of single active regions on solar irradiance can be studied particularly well. The results, presented in Fig. 2, are compared to VIRGO measurements of the total as well as spectral irradiance variations at 862 nm, 500 nm and 402 nm. During the first time period from mid August to mid September 1996 (left panel of Fig. 2) a faculae dominated active region crossed the solar disc. The observed irradiance record (dashed line) shows a distinct double peak which is well reproduced by our model (solid line) in all four spectral regions. The double peak is due to the pronounced center-to-limb variation (CLV) of the facular brightness whose contrast increases strongly towards the solar limb. For comparison, a second reconstruction (dotted line) based on a disc-integrated proxy for the facular emission (i.e. Mg II core-to-wing ratio) fails completely to reproduce the double peak.

The second period from the beginning of November 1996 to the beginning of January 1997 is plotted in the right panel of Fig. 2. This time, a spot dominated active region moved across the solar disc. Again, the reconstruction reliably reproduces the spot-induced depletion of the solar irradiance.

3.2. Long-term variability

When reconstructing irradiance changes on time-scales of the solar cycle great care must be taken in order to include also subtle changes of the active

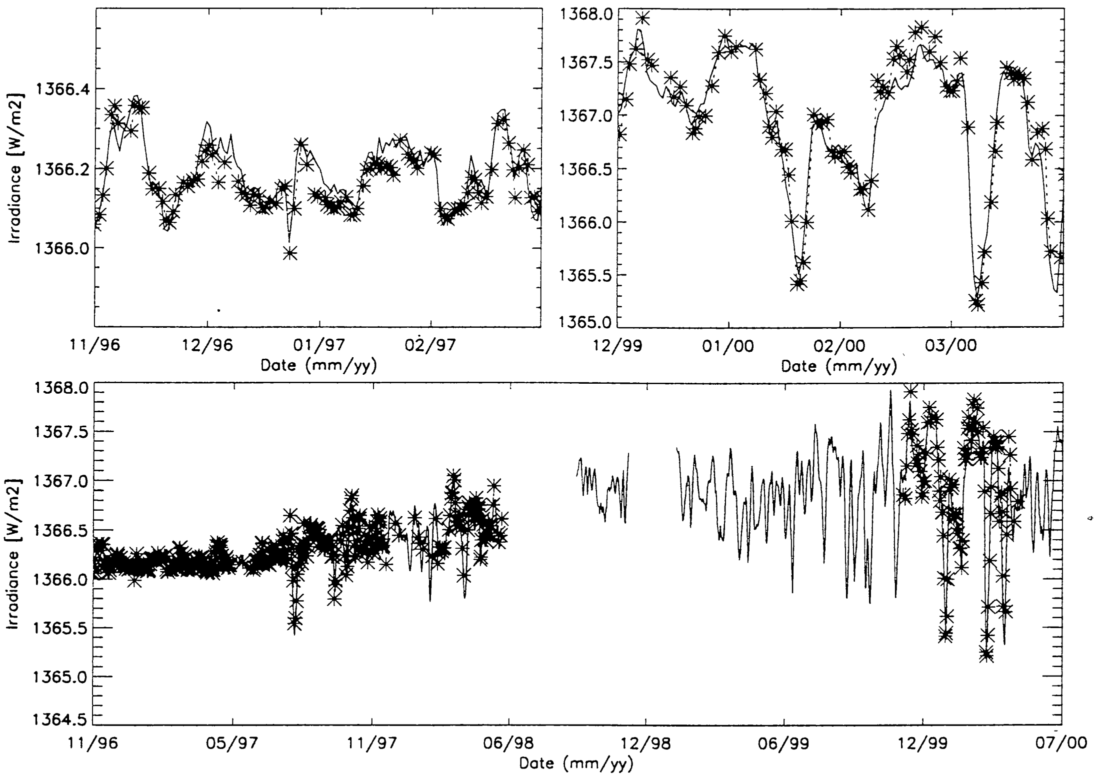

Figure 4. Reconstruction (stars') of total solar irradiance for roughly 700 individual days between the end of 1996 and mid 2000, i.e. from the onset of solar cycle 23 right into its maximum. The irradiance record measured by VIRGO is represented by the solid line. The two panels on the top show a zoom-in to the beginning (left panel) and the end (right panel) of the complete dataset (lower panel), respectively. The model is able to reproduce both, short-term variations on time-scales of days to weeks as well as the longer-term increase of solar irradiance between activity minimum and maximum.

network. The 1-σ noise level of ordinary 1-min magnetograms of MDI is of the order of 20 Gauss. This is not good enough to enable a reliable detection of all or at least most of the network features. Therefore, it is necessary to average over series of 5 or 20 consecutive magnetograms in order to increase the signal-to-noise ratio. Before averaging, the individual 1-min magnetograms have been corrected for differential rotation.

The effect of the averaging on the detection of the active network is presented in Fig. 3. The magnetograms on the upper left (1-min), upper right (5-min) and lower left (20-min), respectively, are enlargements of the frame plotted in the full-disc magnetogram in the lower right. As can be seen, more and more network features become visible when going to longer averages or, equivalently, longer integration times.

Based on these magnetograms, we then reconstructed solar irradiance variations for roughly 700 individual days between the end of 1996 and mid 2000 using exactly the same model atmospheres and input parameters as for the short-term reconstructions described in Sect. 3.1. The results are presented in Fig. 4. The VIRGO measurements are given by the solid line while the reconstructed values are marked by stars.

The lower panel shows the reconstruction over the whole time period. As you can see, the increase between the onset of solar cycle 23 at the end of 1996 and the first half of 2000 when solar activity reached its maximum is very well reproduced. This becomes even more striking when looking at the two enlargements on the top of Fig. 4. The left panel is a zoom-in to the beginning of the selected time period, i.e. near the activity minimum, while the panel on the right is a zoom-in during the time of maximum activity. The quality of the reconstruction is impressive given the simplicity of the employed model and the fact that it possesses only a single free parameter.

The model allows the calculation of solar spectral irradiance variations from 160 nm to 160 000 nm with varying spectral resolution (resolving power better than 200 in the visible). Unfortunately, the long-term sensitivity of VIRGO's sunphotometers is not stable enough to allow a comparison of the reconstructed and measured spectral irradiance records over such a long period. Nevertheless, we present

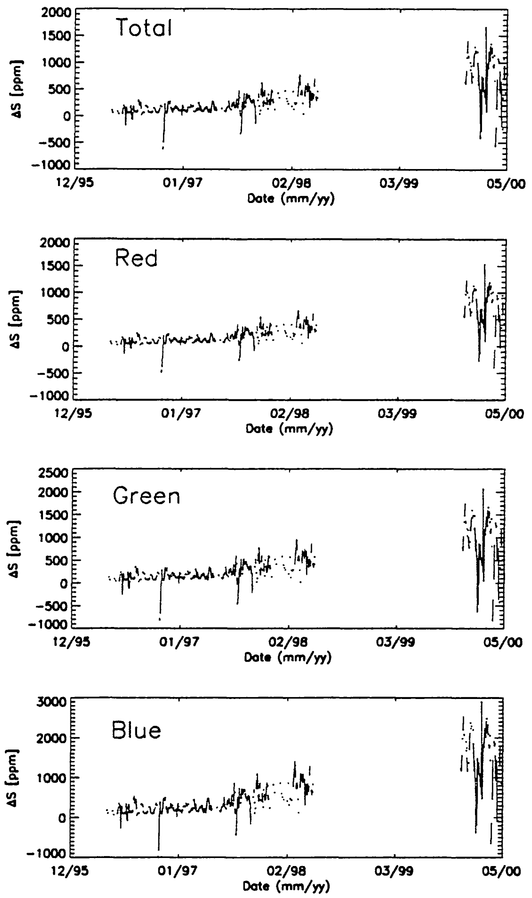

Figure 5. From top to bottom: Reconstructed irradiance variations for the total solar irradiance as well as for the three spectral channels measured by VIRGO which are centered around 862 nm, 500 nm and 402 nm. The irradiance increase between activity minimum and maximum is most pronounced in the blue channel which shows an increase that is about twice as large as the one in the total.

in Fig. 5 the reconstructed irradiance records for the four spectral regions measured by VIRGO, i.e. the total irradiance as well as the irradiance in the three spectral channels centered around 862 nm, 500 nm and 402 nm, respectively. The blue channel shows the steepest rise, reflecting the increase of solar spectral irradiance variability towards shorter wavelengths. While the total and the red channel show comparable variations the increase is the blue is about twice as large as in the total (note the different scaling of the axis').

4. CONCLUSIONS

We have presented a model of solar irradiance variations which is entirely based on the changing solar surface magnetic field. The model is able to reproduce both total and spectral solar irradiance changes on time-scales of days up to the length of the solar cycle. In particular, no additional component is necessary to reproduce the long-term increase of solar irradiance between activity minimum and maximum beside the contributions from sunspots and small magnetic features forming faculae and the active network. In particular, there is no need to distinguish between the contribution of the network and of faculae.

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