Synoptic Solar Physics
ASP Conference Series, Vol. 140, 1998
K. S. Balasubramaniam, J. W. Harvey and D. M. Rabin, eds.

Modelling Spectral Irradiance Variations obtained by VIRGO

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Abstract. We model solar spectral irradiance variations under the assumption that they are produced by sunspots and faculae alone. The results are compared to spectral irradiance measurements obtained by the three-channel sunphotometers (SPM) within VIRGO onboard SOHO between 22 February, 1996 and the end of 1996. The model reproduces the relative magnitudes of the variations at the different wavelengths approximately equally well. Since it also successfully reproduces changes in the UV spectral irradiance our simple model suggests that a large part of the solar irradiance variations is caused by magnetic fields at the solar surface.

1. Introduction

The model we use is based on the assumption that irradiance variations are caused by magnetic features alone. It was originally proposed by Solanki & Unruh (1997) and uses three components, i.e. quiet Sun, sunspots, and faculae to model solar irradiance. Since the model neglects center-to-limb variation of the brightness of magnetic features, irradiance contributions can be described using flux values.

The employed quiet Sun model, F_{qs}, corresponds to a non-gray radiative equilibrium model of Kurucz (1991) with $T_{\rm eff} = 5777$ K. Since the temperature structure of umbrae (Severino et al. 1994, Del Toro Iniesta et al. 1994) and penumbrae is close to that expected from radiative equilibrium, the sunspot model, F_s, is taken from a Kurucz flux spectrum of $T_{\rm eff} = 5250$ K (Kurucz 1991). A slightly modified average plage model of Fontenla et al. (1993) is used to model the third component, i.e. the facular contribution, F_f. The modification is necessary in order to fit the observed UV variations over a complete solar cycle. For that we assume that the radiation from faculae is formed at the same height as in the quiet Sun and neglect the 2-D structure of faculae.

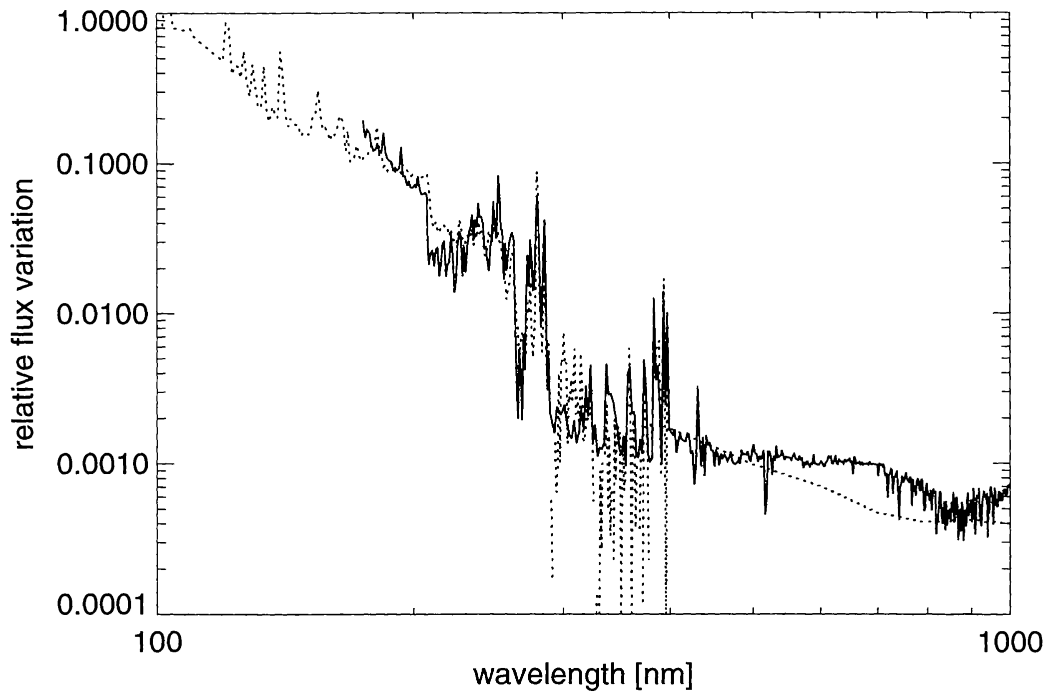

Figure 1. Relative flux variations between solar activity minimum and maximum. Dotted line represents observed and extrapolated values according to Lean et al. (1997) and Lean (1991) while the solid line marks the reconstruction according to Solanki & Unruh (1997) based on the model described in the text. The facular to sunspot filling factor ratio is 16.

We then average over wavelength intervals of 1–40 nm (depending on the considered wavelength range), thus averaging over many lines and continuum (Kurucz fluxes). Finally, the total solar flux is calculated from

$$\begin{aligned} F_{\rm tot}(\lambda) &= (1-\alpha_s-\alpha_f)\cdot F_{qs}(\lambda) \\ &\quad + \alpha_s \cdot F_s(\lambda) \\ &\quad + \alpha_f \cdot F_f(\lambda), \end{aligned} \tag{1}$$

where α_s and α_f represent sunspot and facular filling factors, respectively. The relative flux variation between solar activity minimum and maximum produced by this model is plotted in Fig. 1 (solid line). The dotted curve shows the observed relative irradiance variation for $\lambda < 400$ nm compiled by Lean et al. (1997) and extrapolated to longer wavelengths by Lean (1991). Obviously there is a good agreement between observations and the model.

2. VIRGO Measurements

Sunphotometers (SPM) within VIRGO measure spectral irradiance variations at three different wavelength, i.e. at 402 nm (blue channel), 500 nm (green channel) and 862 nm (red channel) with a bandwidth of 5 nm each. In addition, VIRGO also records total irradiance values obtained by the active-cavity radiometers PMO6-V. Details about the observations and instruments are given by Fröhlich et al. (1997a, 1997b).

We reconstruct relative spectral irradiance variations, i.e. deviations from the mean, for the time between 22 February, 1996 to the end of 1996. We are currently in a phase of low solar activity and the irradiance measurements show only minor variations. Nevertheless, enhanced facular emission as well as a few dips due to the passage of sunspots across the solar disk are clearly recognizable.

3. Modelling VIRGO Measurements

Temporal variations of sunspots and faculae are mimicked using time-series of projected sunspot areas, $A_s(t)$, and Mg II core-to-wing ratios, $Mg(t)$, respectively. In Eq. (1) we set

$$\begin{aligned} \alpha_s(t) &= a_s \cdot A_s(t) \\ \alpha_f(t) &= a_f \cdot Mg(t) \end{aligned} \quad (2)$$

where the parameters a_s and a_f are to be determined by least-square fitting of the observational time-series. $F(\lambda, t)$ is obtained by combining Eqs. (1) and (2). Note that only the ratio between different color channels provides a direct test of the employed model of solar spectral irradiance variations. The goodness to which the temporal behavior of the irradiance variations is reconstructed, however, is a consequence of the selected proxies only and is limited by their quality and completeness.

Then we calculate relative irradiance variations according to

$$\Delta^c(t) = \frac{F^c(t) - \langle F^c(t) \rangle_t}{\langle F^c(t) \rangle_t} \quad (3)$$

where

$$F^c(t) = \int F(\lambda, t) \cdot K^c(\lambda) \quad d\lambda. \quad (4)$$

K^c is the transmission function of the filter-radiometer for each color channel, where c marks the considered wavelength range, i.e. total irradiance, 862 nm (red), 500 nm (green) and 402 nm (blue), respectively, and $\langle \cdot \rangle_t$ stands for averaging over time.

Fig. 2 shows a reconstruction of total (top panel) and spectral irradiance (lower three panels). Observed data are dotted while reconstructed data are solid. The ratio of faculae to spot filling factor used in this plot is 20:1. This filling factor ratio agrees very well with ratios determined directly from observations by Chapman et al. (1997). The employed solar model is able to reproduce the observed increase in spectral variability (RMS values) from longer to shorter wavelength ranges, i.e. from the red to the blue color channel.

The ratios of the RMS values of total to spectral irradiance variations over the considered time period of both the observed and reconstructed time-series are given in Table 1. The RMS of the blue channel is slightly too low compared to VIRGO measurements. Introducing center-to-limb variations may help to solve this problem since limb-brightening of faculae tends to increase the variability

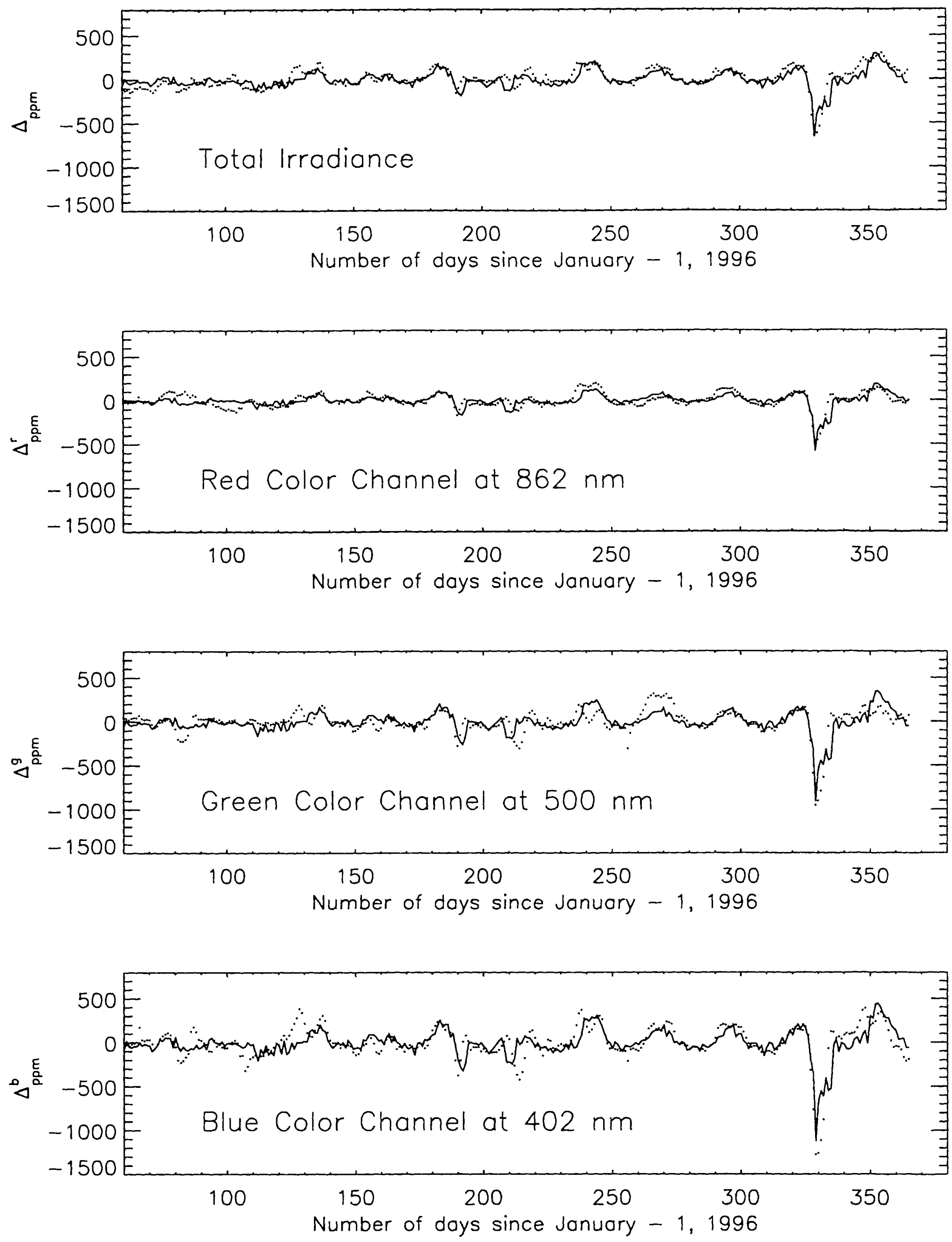

Figure 2. Reconstruction of total and spectral relative irradiance variations obtained by VIRGO for the year 1996. The employed solar model is able to fit both total and spectral irradiance about equally well. In particular, the model reproduces the increase of spectral variability (RMS values) from longer (red channel) to shorter wavelength ranges (blue channel) of the spectrum.

in the blue channel. Note that for a_s we obtain almost exactly unity, suggesting that the effective temperature chosen to represent sunspots is appropriate.

Table 1. Comparison between modelled and observed RMS variations of the four color channels.

	$\sigma_{red}/\sigma_{tot}$	$\sigma_{green}/\sigma_{tot}$	$\sigma_{blue}/\sigma_{tot}$
VIRGO	0.775	1.279	1.845
Model	0.771	1.315	1.605

4. Results

Standard sunspot and facular models can reproduce the VIRGO data, in particular the ratios between the various color channels, relatively well (see Table 1). These same models also reproduce the ratio between facular and sunspot filling factors and the spectral dependence of UV irradiance variations (see Fig. 1).

The 3 SPM color channels sample almost the same heights in the solar atmosphere and hence cannot give any information on temperature gradients of facular or sunspot models. On the other hand, together with observed filling-factor ratios, the SPM observations can constrain the temperature values of faculae in the low photosphere (those of sunspots are already well constrained from other sources). We find $\Delta T \approx +50K$ compared to quiet Sun values at the height at which the radiation sampled by the SPMs is formed.

The fact that our simple model reproduces a combination of VIRGO, ACRIM (not discussed in this paper) and UV (SUSIM) irradiance observations, together with facular and sunspot filling factor observations strongly suggests that at least on time-scales of the solar cycle or less, surface magnetic features are responsible for the major part of solar irradiance variations.

Acknowledgments. This work was supported by the Swiss Nationalfonds under NF grant No. 21–40428.94 and the Austrian Science foundation under grant No. S7302. The VIRGO team is acknowledged for providing data. VIRGO is an investigation on the Solar and Heliospheric Observatory, SOHO, which is a mission of international cooperation between ESA and NASA.

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