Pergamon
www.elsevier.com/locate/asr

*Adv. Space Res.* Vol. 29, No. 12, pp. 1933–1940, 2002

Printed in Great Britain
0273-1177/02 $22.00 + 0.00
PII: S0273-1177(02)00238-7

# HOW MUCH OF THE SOLAR IRRADIANCE VARIATIONS IS CAUSED BY THE MAGNETIC FIELD AT THE SOLAR SURFACE?

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## ABSTRACT

The contribution to total solar irradiance variations by the magnetic field at the solar surface is estimated. Detailed models of the irradiance changes on the basis of magnetograms show that magnetic features at the solar surface account for over 90% of the irradiance variations on a solar rotation time scale and at least 70% on a solar cycle time scale. If the correction to the VIRGO record proposed by Fröhlich & Finsterle (2001) is accepted, then magnetic features at the solar surface are responsible for over 90% of the solar cycle irradiance variations as well.


## INTRODUCTION

The evidence that the solar irradiance varies on time scales up to that of the solar cycle is by now overwhelming (e.g., Fröhlich 2000). The physical cause of the irradiance variations remains a topic of intense investigation, however. Although considerable evidence has accumulated that the solar surface magnetic field is largely responsible for the variations of total solar irradiance (TSI; e.g. Chapman et al., 1984; Foukal & Lean, 1986, 1988, 1990; Fligge et al., 1998), much of the evidence is rather indirect, based as it is on chromospheric proxies of the magnetic field (with the exception of Chapman et al., 1984). Such proxies sample other layers of the solar atmosphere than the one from which most of the irradiance or its variability comes from. They also do not take the important centre-to-limb variations of the brightness of magnetic features into account properly. In addition, other sources of irradiance variations have been proposed or are at least conceivable. These include the r-mode oscillations driven by solar rotation (Wolff & Hickey, 1987a,b) changes in the heat flux caused by the toroidal magnetic field at the bottom of the convection zone (thermal shadowing, Parker, 1987), subtle changes in the convection properties produced by these magnetic fields, by fields emerging through the convection zone (Parker, 1995), by torsional oscillations or other means. It has also been argued on the basis of limb photometer observations that faculae cannot be responsible for most of the brightness increase from solar activity minimum to maximum (Kuhn et al., 1988).

There is thus a strong need for more detailed models based directly on the magnetic field at the solar surface in order to identify the main mechanism responsible for total irradiance variations.

A knowledge of this mechanism is necessary in order to reconstruct the irradiance at epochs prior to the availability of direct measurements. Such longer term irradiance trends are the important quantity, however, for the comparison of solar irradiance with terrestrial climate.

Here we give an overview of recent efforts to improve this situation and quantify the fraction of solar irradiance variations caused by solar surface magnetism. When making such an estimate it is important to distinguish between the 27-day solar rotation time scale and the 11-year solar cycle time scale. Irradiance variations on even longer time scales are possible and there is indirect evidence that such secular trends exist (White et al., 1992; Lean et al., 1992, 1995; Zhang et al., 1994). However, although it is possible to speculate on the nature of the drivers it is too early to make quantitative estimates of such secular trends from any other cause than solar surface magnetism variations. Long term trends will therefore not be discussed here any further.

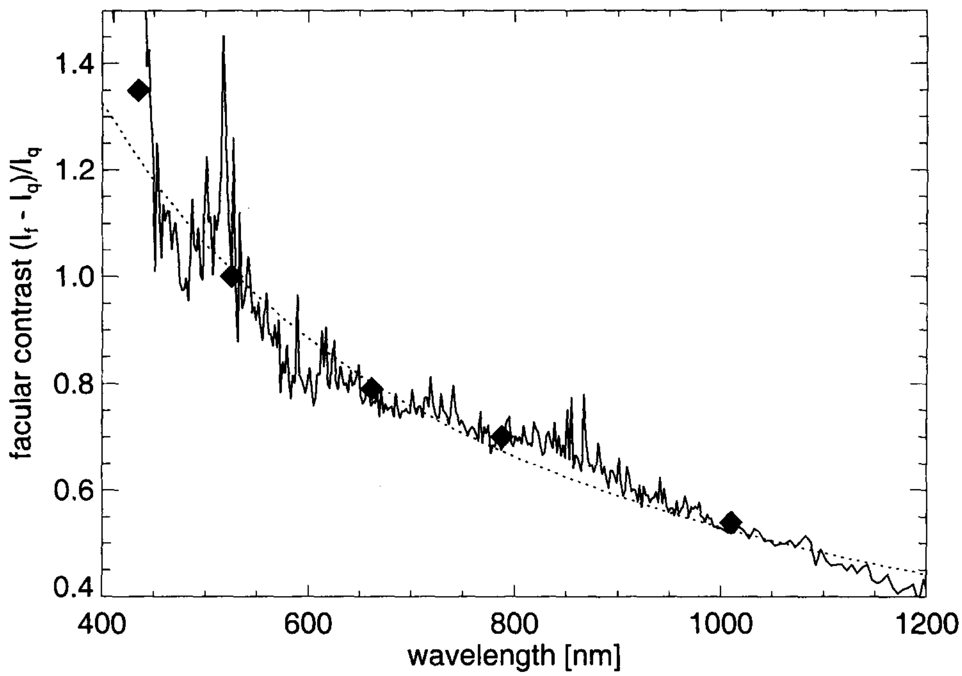


Fig. 1. The spectral variation of the facular contrast. The diamonds are the data from Chapman & McGuire (1977). They were obtained from measurements between 16″ and 53″ ($\mu$ = 0.18 to 0.33). The dotted line shows the inverse wavelength fit suggested by Chapman & McGuire.

## MODEL

The main assumptions underlying the model on which the results described here are based may be written as:

1. The irradiance change is entirely caused by the magnetic field at the solar surface, i.e. the magnetic field that can in principle be detected with magnetograms. The term 'in principle' implies the magnetic field seen if the magnetograms are sufficiently sensitive, have sufficiently high spatial resolution and can also sense transverse magnetic fields.

2. It is sufficient to divide the solar photosphere into three components: quiet Sun (denoted by subscript $q$), sunspots ($s$) and faculae ($f$). We thus implicitly assume that a single component provides an adequate description of both active region faculae and the network. We also neglect the fine structure underlying faculae and the network (they are composed of myriads of discrete flux tubes with diameters less than a few hundred km), so that each atmospheric component can be represented by a plane-parallel atmosphere. Note that for a better reproduction of the data we have also considered the umbrae and penumbrae of sunspots separately.

3. It is sufficient to know the intensity $I(\mu, \lambda)$ of each component and the fraction of the solar surface that it covers (filling factor $\alpha(\mu, t)$) at a particular $\mu = \cos\theta$ (where $\theta$ is the heliocentric angle) and time $t$ for a complete description. In particular, we assume that the intensities $I_q$, $I_f$ and $I_s$ are independent of time $t$, while $\alpha_q$, $\alpha_s$, $\alpha_f$ do not depend on wavelength $\lambda$. We also assume that $I$ does not depend on azimuth relative to the centre of the solar disc.

Assumptions 2 and 3 are only approximately fulfilled, since e.g. sunspot umbral brightness is time dependent (Albregtsen & Maltby 1978) and network flux-tubes are hotter than those in plage (e.g. Solanki 1996). We plan to relax them in future investigations. The $I(\mu, \lambda)$ are calculated using the ATLAS9 code of Kurucz and opacity distribution

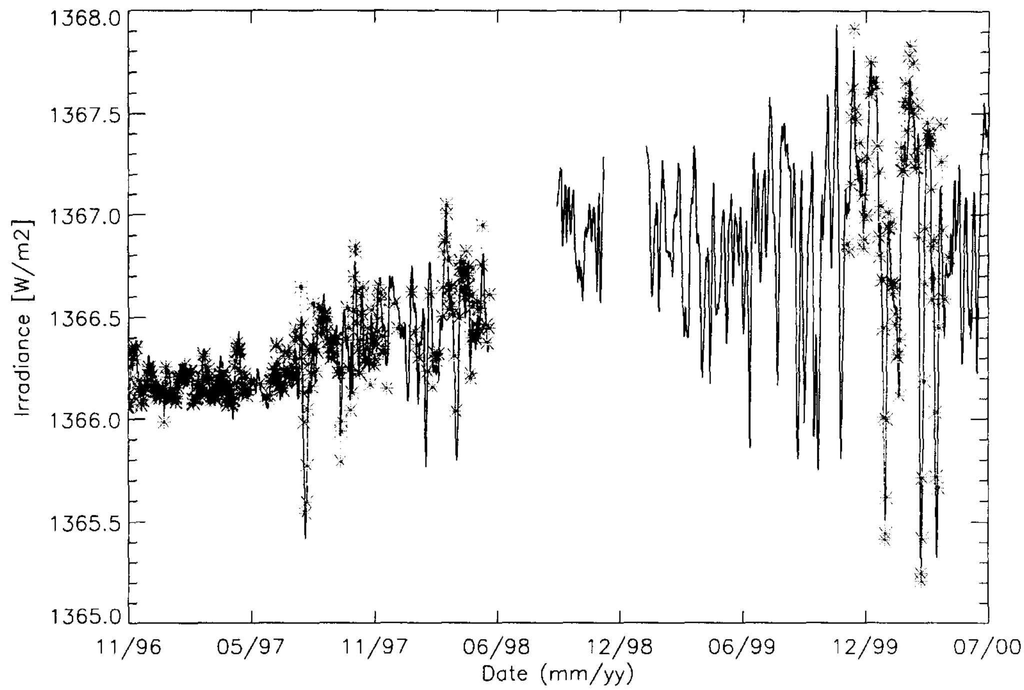


Fig. 2. Total solar irradiance as measured by VIRGO on SOHO (solid curve) and as reconstructed from MDI magnetograms using the model described in Sect. 2 (asterisk) vs. time.

functions (ODFs, obtained through the Collaborative Computing Project No.7, i.e. CCP7) from plane-parallel model atmospheres of the quiet Sun, sunspots and faculae. The models for sunspots and quiet Sun are standard, corresponding to the FAL-C model (Fontenla et al., 1993) and an appropriate radiative equilibrium model of Kurucz (1992a,b,c; cf. Severino et al., 1994; Solanki, 1997), respectively. For the faculae we have used a somewhat modified version of FAL-P. Details are given by Unruh et al. (2000) and Figure 1 shows how the intensity spectrum calculated from this modified facular model (solid curve) compares with the observed spectrum (Chapman and McGuire 1977, filled diamonds). Using these stratifications we obtain the intensities $I_q(\mu, \lambda)$, $I_s(\mu, \lambda)$ and $I_f(\mu, \lambda)$ for the quiet Sun, sunspots and faculae as a function of wavelength $\lambda$ and location $\mu$.

The filling factors $\alpha(\mu, t)$ are taken from daily full-disc MDI magnetograms and continuum images. First we determine $\alpha_s$ from the continuum images (with $\alpha_s$ = the ratio of the measured area of sunspots to the area of the full solar disc). The $\alpha_f$ is determined from the magnetograms, whereby only those points are chosen which simultaneously satisfy the criteria that 1) the magnetogram signal is larger than three times the noise level, and 2) they do not lie within sunspots. To maintain a homogeneous and low noise level only 5-minute averages over consecutive 1-minute magnetograms are employed.

Finally, the irradiance or equivalently the flux of the whole Sun is calculated using the following equation:

$$F(\lambda, t) = \int_0^1 \left[\alpha_s(\mu, t) I_s(\mu, \lambda) + \alpha_f(\mu, t) I_f(\mu, \lambda) + \left(1 - \alpha_s(\mu, t) - \alpha_f(\mu, t)\right) I_q(\mu, \lambda)\right] \mu \, d\mu. \quad (1)$$

The only free parameter in the model that is not already constrained by independent observations is a scaling factor required to convert MDI magnetogram signal strength into $\alpha_f$. This free parameter is determined by requiring that the model should reproduce the irradiance variations produced by the passage of an active region across the solar disc. Using the same factor the whole VIRGO time series until the loss of SOHO is then modelled.

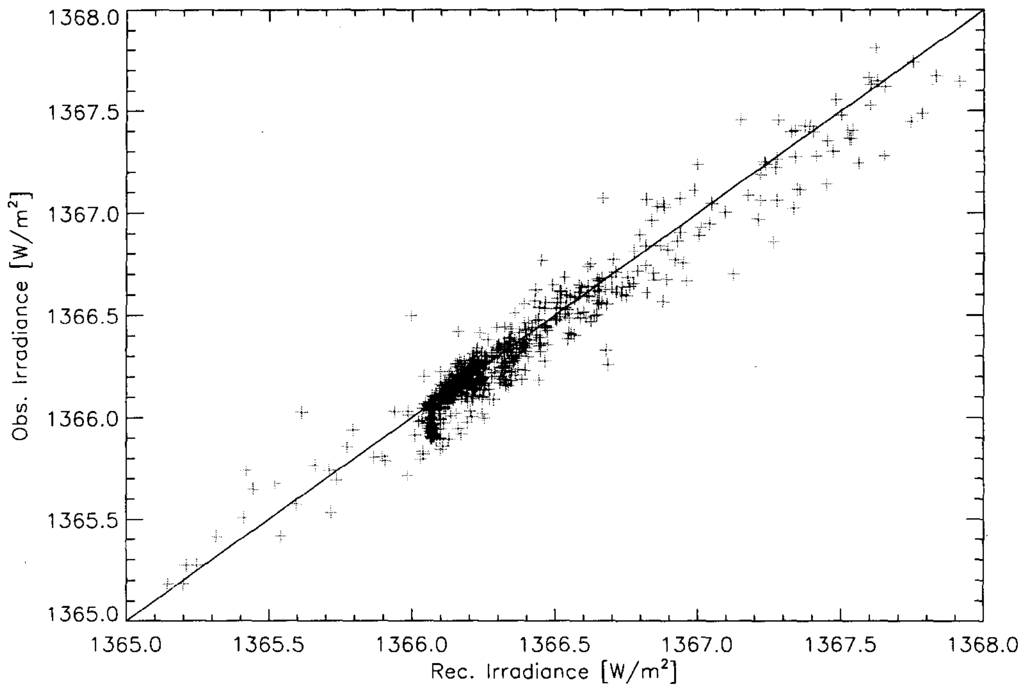


Fig. 3. Measured total solar irradiance (TSI) vs. modelled TSI. the solid diagonal line represents the expectation values for a perfect model fit.

## RESULTS

The results for the period between November 1996 and mid 2000 is plotted in Figure 2 (solid curve: VIRGO measurements of TSI; stars: modelled TSI). Note that the new VIRGO level 2 data are employed, i.e. data which have been corrected for bias according to the proposal of Fröhlich and Finsterle (2000) Without this correction only about 70% of the irradiance variations over the solar cycle is reproduced by the model. The excellent correspondence between the two quantities is confirmed by plotting the measured TSI against the reconstructed value (Figure 3, crosses). The solid line indicates the relationship expected if the reconstruction would be perfect, the dashed line is a linear regression through the crosses. Obviously very little bias is present in the reconstruction.

The model is also capable of reproducing other global quantities, as described below. In Figure 4 (Fligge et al., 2000), respectively, one and two month time series of VIRGO TSI, as well as of the irradiance in the three VIRGO colour channels are shown (dashed curves). Also plotted are the reconstructions of all four records (solid curves). Similarly, in Figure 5 we compare the measured and modelled relative change in the solar UV spectrum between solar activity maximum and minimum. As before, the model gives a reasonable representation of the data (Solanki and Unruh, 1998; Unruh et al., 2000). Note, however, the log-log scale in Figure 5, which downplays some differences between the two curves, particularly in strong UV lines, which are not well represented by the assumption of LTE made in the model. On the other hand the data are very noisy between 300 and 400 nm, so that discrepancies with the model in this wavelength range are probably not significant. This diagnostic is very sensitive to the change in temperature structure of the solar atmosphere over the solar cycle. The result of varying the solar effective temperature by 1.0° over the cycle is also plotted in Figure 5 (dashed curve). This value has been chosen because then the TSI changes by the observed amount of 0.1%. The poor correspondence with the observations in the UV is evident in this case, effectively ruling out a global variation of solar properties as the cause of solar irradiance variations.

The model described in Sect. 2 also reproduces further parameters such as the observed variation of the facular to sunspot area ratio over the solar cycle (Chapman et al., 1997; Fligge et al., 1998) or the change in the line blanketing over the solar cycle (Mitchell and Livingston, 1986; Unruh et al., 2000). The line blanketing is a measure of the

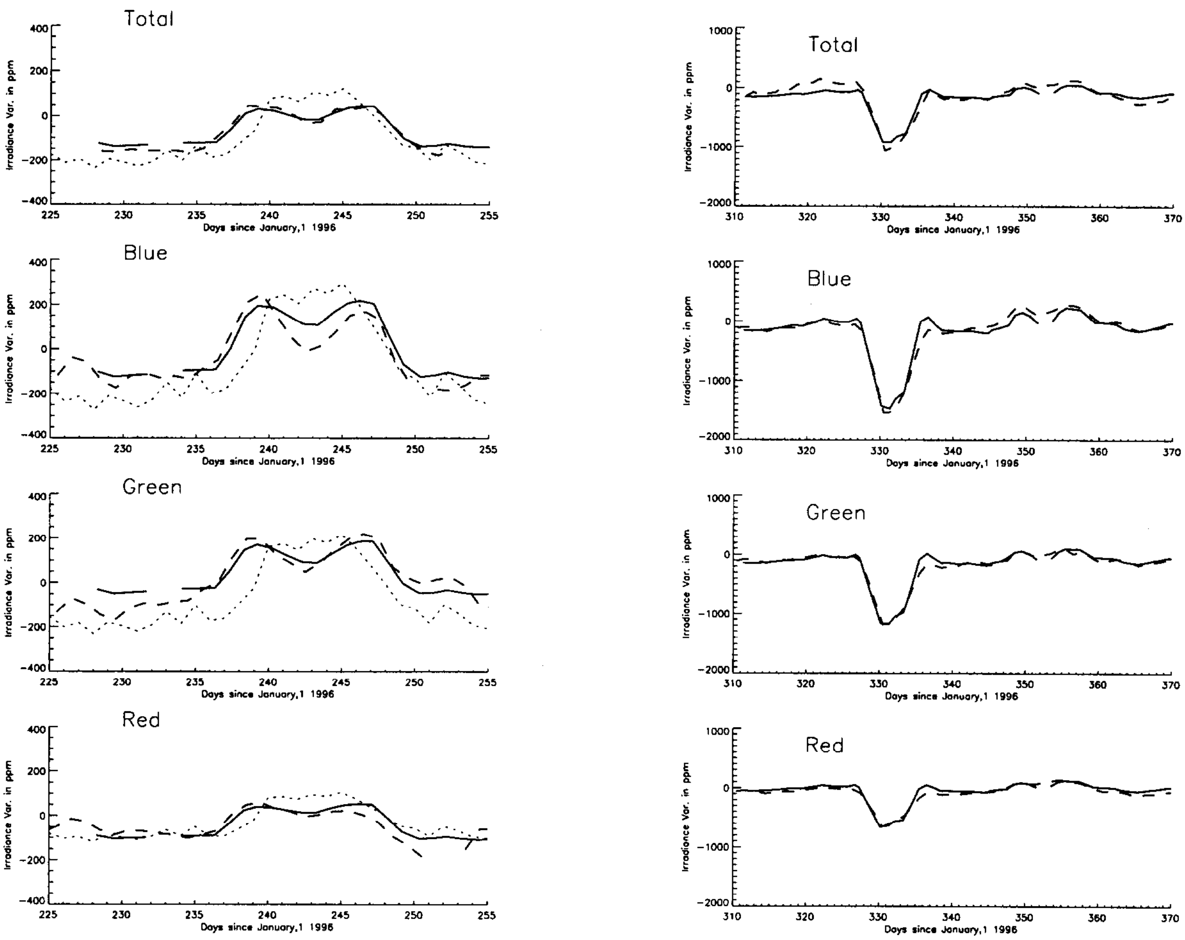


Fig. 4. Comparison between measured (solid) and modeled (dashed) solar total and spectral irradiance variations for the time between 15 August and 15 September 1996 (left panel) and 6 November 1996 and 6 January 1997 (right panel), respectively. Plotted are (from top to bottom) the total irradiance, and the spectral irradiance variations measured in the blue, green and red color channels of VIRGO. 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)

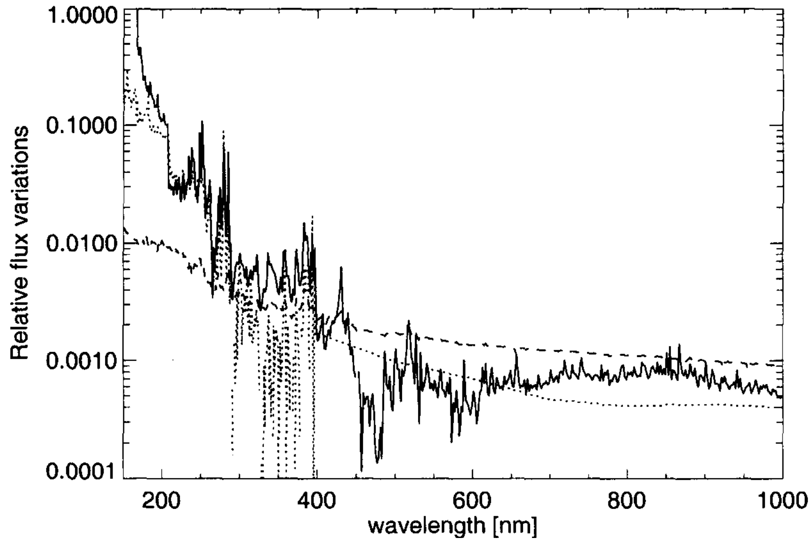


Fig. 5. Relative flux variation obtained from a 3-component model (solid line) vs. wavelength. The facular component is described by the altered FAL-P model and the facular and sunspot filling factors are 0.032 and 0.0027, respectively. The dotted curve shows the observed relative irradiance variation for $\lambda < 400$ nm between activity minimum and maximum vs. wavelength, compiled by Lean et al. (1997) and extrapolated to longer wavelength by Lean (1991). The dashed curve denotes the relative flux variations if the effective temperature of the Sun is 1.0° higher at activity maximum than at minimum. Clearly, the reproduction of the observations in the UV is much poorer.

fraction of the continuum radiation observed by spectral lines.

The success of our model supports the conclusion that the magnetic field at the solar surface is responsible for over 90% of the TSI variability at time scales of the solar rotation and the solar cycle.

This excellent correspondence between model and data is only achieved if we accept the correction to the irradiance record in the second half of 1996 proposed by Fröhlich and Finsterle (2001). There is, however, a significant discrepancy between the models and the VIRGO measurements in the second half of 1996, if this correction is not carried out. Whereas the reconstructed TSI shows a flat minimum in that period, the uncorrected VIRGO signal increases by 0.3 W $m^{-2}$ in that time. The signals of individual active regions superimposed on this trend is similar in both records. Due to this discrepancy the lower limit for the contribution made by surface magnetism to the TSI variations over the cycle drops to 70% in the absence of such a correction.

## CONCLUSION

By comparing the output of models based on the properties of photospheric magnetic features with the measurements of total solar irradiance variations it is possible to estimate the fraction of these variations due to the surface magnetic field. We find that over 90% of the short term variations (i.e. those on a solar rotation time scale) can be explained by solar surface magnetism. On a longer time scale this fraction remains at 90% once the correction to VIRGO data proposed by Fröhlich and Finsterle (2001) is carried out.

These fractions must be considered to be lower limits since a part of the discrepancy between measurements and model is due to measurement uncertainties and shortcomings in the model due to the simplifying assumptions (Sect. 2). A more detailed discussion of the points in the model that may be improved will be given in a forthcoming paper by Fligge et al. (2001). Further improvements in the measurement techniques and the modelling, as well as a reconstruction of longer time series will lead to improved estimates of the contribution of surface magnetism to irradiance variations. Nevertheles even the simple modelling we have carried out suggests that mechanisms not directly related to the magnetic field at the solar surface do not contribute more than 10% to the measured irradiance variations (at time scales between days and a decade).

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