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A model of the wavelength dependence of solar irradiance variations

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Abstract. The variation of the solar irradiance over the solar cycle has a strong wavelength dependence, being larger at shorter wavelengths. Here we present simple models of the spectral dependence of irradiance variations between solar activity maximum and minimum. We find that the observations (which concentrate on the UV) cannot be reproduced by a change in effective temperature of the Sun (or of parts of its surface) alone. We can, however, reproduce the data with either a 2-component or a 3-component model, of which one component is the quiet Sun, another is a facular component, and the third (in the case of the 3-component model) represents the temperature stratification of sunspots. The facular component is found to be very close to the facular models F or P of Fontenla et al. (1993). The success of these models supports the assumption underlying many studies of total solar irradiance variations that these are caused mainly by magnetic fields at the solar surface. Our investigation also allows an improved estimate of the relative contribution of the various layers in the solar photosphere and of the different wavelength regions to the total irradiance variations.

Key words: Sun: photosphere – Sun: UV radiation – Sun: faculae – Sun: activity

1. Introduction

Satellite observations of the solar total irradiance (the wavelength-integrated flux per unit area measured on the Earth) show that it varies on a number of time scales, with the variation over the 11-year solar cycle being particularly prominent (Willson & Hudson 1988, 1991, Kyle et al. 1994, Fröhlich 1994, Lean 1997, Lean et al. 1997). A number of causes have been proposed to explain these observations. Quite successful have been models which assume that the total (i.e. wavelength-integrated) irradiance variations observed in the course of a solar cycle are due exclusively to the change of the amount and concentration of magnetic flux on the solar surface (Foukal & Lean 1986, 1988, 1990, Pap et al. 1994, Chapman et al. 1996, see Spruit 1994 for theoretical arguments in favour of such models). They assume that the magnetic contribution to the irradiance variations can be divided into two categories, a darkening due to sunspots and a brightening due to faculae. Such models can reproduce much (although not all) of the variation of the solar irradiance on time scales of months to years.[1] It is unclear to what extent the remaining discrepancy is due to shortcomings in the models, uncertainties in the underlying data (sunspot areas, facular proxies), or errors in the irradiance measurements. This is particularly unfortunate since a number of proposals for explaining solar irradiance variations in terms of, e.g., convection cell changes (Endal et al. 1985, Fox & Sofia 1994), oscillations (Wolff & Hickey 1987a,b), or internal magnetic fields (Dicke 1979) have also been made.

In addition to the temporal variations, a successful model also has to satisfy the observations of the wavelength dependence of the irradiance variations between, e.g., the solar cycle maximum and minimum. Such observations have been obtained mainly in the UV by various instruments and teams (e.g., London et al. 1993, Brueckner et al. 1993, Cebula et al. 1994, Rottman et al. 1994). The irradiance variability in the UV during solar cycle 21 has been compiled by Lean (1991) and Lean et al. (1997). The relative irradiance change between solar activity minimum and maximum was kindly provided to us by her and is plotted in Fig. 1 (dotted curve). Note, however, that the observed flux variations at $\lambda > 400$ nm are estimates.

In this paper we attempt in a very simple fashion to determine the height variation of the temperature in 2- and 3-component models of the quiet and active Sun which reproduce these observations. We thereby hope to shed light on the role of surface magnetism in influencing solar irradiance relative to other possible mechanisms. Another aim is to determine the

[1] Most of the long-term (decades to centuries) reconstructions of solar irradiance are also based on models with similar assumptions (e.g. Foukal & Lean 1990, Lean et al. 1995).

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contribution of different height and wavelength ranges to the total irradiance variation.

In Sects. 2, 3 and 4 we describe three different sets of models and their results, which we compare with the observations. We only compare *relative* irradiance changes, i.e. $(S_{\rm a}^\lambda - S_{\rm q}^\lambda)/S_{\rm q}^\lambda$, where $S_{\rm a}^\lambda$ is the wavelength-dependent irradiance of the active Sun (i.e. near the time of the maximum of the solar activity cycle) and $S_{\rm q}^\lambda$ that of the quiet Sun (i.e. near activity minimum). Therefore, we can use fluxes F^λ instead of irradiances for the modelling, since the relative flux variation is given by

$$\frac{\Delta F^\lambda}{F^\lambda} = \frac{F_{\rm a}^\lambda - F_{\rm q}^\lambda}{F_{\rm q}^\lambda} = \frac{S_{\rm a}^\lambda - S_{\rm q}^\lambda}{S_{\rm q}^\lambda} = \frac{\Delta S^\lambda}{S^\lambda}. \quad (1)$$

Note that all the quantities in Eq. 1 depend significantly on λ. $F_{\rm a}^\lambda$ and $F_{\rm q}^\lambda$ are the flux counterparts of $S_{\rm a}^\lambda$ and $S_{\rm q}^\lambda$.

2. Enhancement of the effective temperature

The observed flux spectrum of the average quiet Sun (Neckel & Labs 1984, Labs et al. 1987) is well described by the flux emerging from the non-grey radiative equilibrium model with effective temperature $T_{\rm eff}$ = 5777 constructed by Kurucz (1991, 1992), cf. Neckel (1994). This is the basic flux spectrum that we use as a starting point for each model. We denote the flux from this model with $F_{\rm q}^\lambda$.

2.1. Single component model: A homogeneous Sun

We first consider the effect of changing $T_{\rm eff}$ of the Sun while allowing the temperature stratification to remain in radiative equilibrium. The spectrum at this new $T_{\rm eff}$ is obtained by interpolating between F^λ of different $T_{\rm eff}$ of Kurucz's grid of flux spectra. We then determine the relative flux $\Delta F^\lambda/F^\lambda$and compare with the corresponding observed values under the condition that

$$\frac{\Delta F^t}{F^t} = \frac{\int \Delta F_{\rm model}^\lambda d\lambda}{\int F_{\rm q,model}^\lambda d\lambda} = \frac{\int \Delta S_{\rm obs}^\lambda d\lambda}{\int S_{\rm q}^\lambda d\lambda} = \frac{\Delta S^t}{S^t}. \quad (2)$$

The $\Delta S^t/S^t$ values we use were obtained by the ACRIM (Willson & Hudson 1991) and ERB (Kyle et al. 1994) instruments, which give a total relative variation of approximately 0.1% and 0.2%, respectively. The variation due to the ERB instrument is smaller, however, if the corrections proposed by Lee et al. (1995) and Chapman et al. (1996) are taken into account. We therefore consider 0.1% to be the value our models should approximately reproduce.

The $T_{\rm eff}$ increase that is required to achieve a solar irradiance variability of about 0.1% is 1.5 K. The resulting $\Delta F^\lambda/F^\lambda$ as a function of wavelength is plotted in Fig. 1 (solid curve) together with the observed variations (dotted curve). The variability is largely underestimated in the UV and overestimated in the visible and IR by this model.

Similarly, we have constructed a model in which the temperature stratification of the active sun is simply offset by a height-independent amount relative to the quiet-sun temperature structure. The result of this model is almost indistinguishable from the solid curve in Fig. 1 and has therefore not been plotted.

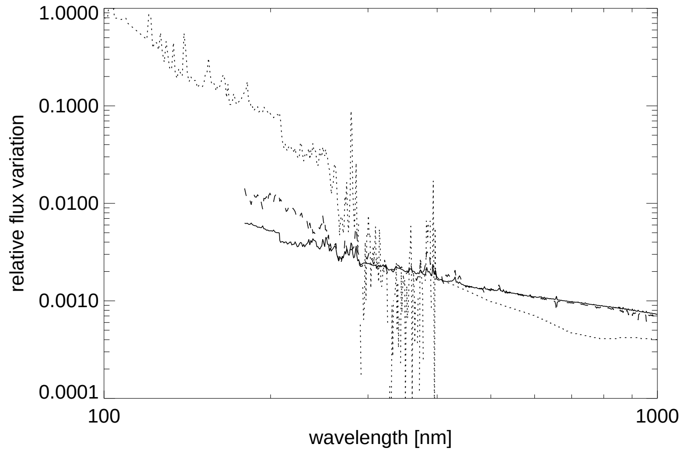

Fig. 1. The dotted curve shows the observed relative irradiance variation for $\lambda < 400$ nm between solar activity minimum and maximum vs. wavelength, compiled by Lean et al. (1997) and extrapolated to longer wavelengths by Lean (1991). The solid curve denotes the relative flux variation if the effective temperature, $T_{\rm eff}$, of the Sun is 1.5 K higher at activity maximum than at minimum. The dashed line is for a 2-component model with a bright (active) component having $T_{\rm eff}$ = 6000 K and a filling factor of 0.6 %

2.2. Two-component model

Next, we considered two atmospheric components, one with the quiet-sun temperature, the other with an enhanced effective temperature $\Delta T_{\rm eff}$, covering a fraction α of the projected solar surface area. The flux measured at activity maximum is hence:

$$F_{\rm a}^\lambda = (1-\alpha)F_{\rm q}^\lambda + \alpha F^\lambda(T_{\rm eff} + \Delta T_{\rm eff}). \quad (3)$$

We now have two free parameters, α and $\Delta T_{\rm eff}$. For increasingly smaller α and correspondingly larger $\Delta T_{\rm eff}$ the results of this model lie closer to the observed curve. However, in order to obtain reasonable agreement, α has to be considerably less than even the smallest α value we have considered, α = 0.006. Such a filling factor is an order of magnitude too low, since we know that magnetic plage (as seen e.g. in Ca II K) cover more than 4 % of the solar surface during activity maximum (Foukal 1996). The dashed line in Fig. 1 shows $\Delta F^\lambda/F^\lambda$for α = 0.006 and an active component with $T_{\rm eff}$ = 6000 K. Note that the quiet-sun component which we use reproduces the mean solar spectrum at activity minimum, i.e. it already includes the influence of the magnetic network, which remains relatively unchanged between activity minimum and maximum (cf. Harvey 1994).

Fig. 1 clearly demonstrates that the change in temperature of the solar atmosphere between activity maximum and minimum must be height dependent.

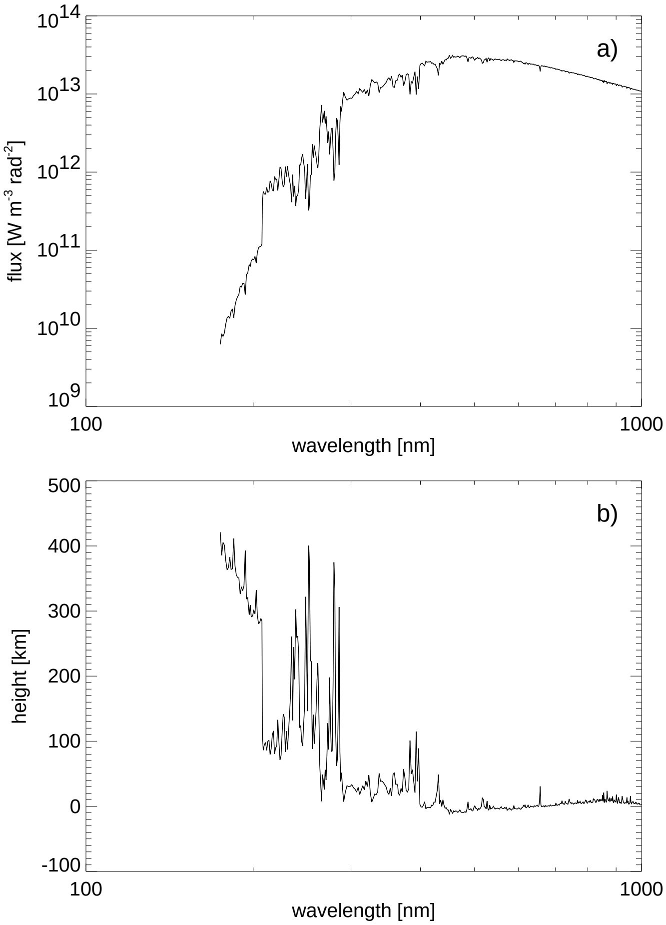

Fig. 2. a Flux spectrum F_{q}^{λ} resulting from the quiet-sun model of Kurucz (1991). **b** Formation height of the "black-body" flux as a function of wavelength (see text).

3. Height-dependent temperature enhancement

Next we consider a 2-component model of which one component is the quiet Sun (F_{q}^{λ}) and the other is a bright facular component that is allowed to have a different temperature gradient from the quiet Sun.

The Kurucz spectrum for the Sun (T_{eff} = 5777 K, $\log g$ = 4.44) was again used to represent the quiet solar flux, F_{q}^{λ} (Fig. 2a). In the photosphere the temperature stratification of this model is very similar to that of the quiet-sun model of Fontenla et al. (1993), henceforth called FAL-C (the reason for using the FAL-C model is given below). We assume that the flux spectra of the two models are also the same. We expect this assumption to be largely fulfilled for the wavelengths we consider.

Next we describe the steps leading to our estimate of the flux spectrum of the facular component. We begin with F_{q}^{λ}. In a first step we convert it into temperature (at each wavelength individually) using the Planck function and determine the height at which this radiation is formed by interpolating in the temperature stratification of FAL-C. The formation height of the quiet-sun flux as a function of wavelength is shown in Fig. 2b. We have also determined the formation height using the Kurucz solar model atmosphere, and find similar results to those plotted, which suggests that the use of FAL-C is a valid assumption.

The flux in the facular regions, F_{f}, can be calculated from the formation height using the inverse procedure to the one described above. Each height in the facular atmosphere is associated with a temperature in the facular model atmosphere. This temperature is then converted into the corresponding black-body flux at each wavelength point which corresponds to F_{f}^{λ}. We assume that F_{f}^{λ} is formed at the same average height (in the facular atmosphere) as F_{q}^{λ} is formed in FAL-C.

Instead of constructing a facular model from scratch we start with the facular models F and P of Fontenla et al. (1993), compare their results with the observations and, if necessary, change them somewhat in order to obtain an improved correspondence. In the following we call these facular models FAL-F and FAL-P, respectively. This choice dictates our use of FAL-C to describe the quiet-sun temperature stratification, since relative differences in temperature are more important than absolute values. The temperature stratifications of the three models FAL-C, F and P are plotted in Fig. 3.

It is well known that 2-component models of faculae (composed of flux tubes with a height dependent cross-section and a non-magnetic atmosphere which can differ from the quiet Sun) are more realistic than the plane-parallel atmospheres we employ. The complexity of flux-tube models precludes their use here (multi-ray radiative transfer calculations would be required at every sampled wavelength). The question then arises which of the numerous single-component facular models available in the literature one should employ. The exact choice of such a model is fortunately not so critical for two reasons. Firstly, most 1-component facular models are similar in the sense that they correspond closely to the quiet Sun in their lower photospheric layers and are hotter in their higher layers. The numerical value of the temperature enhancement depends on the spatial resolution of the observations underlying the empirical models and the types of regions observed. However, our results only depend on the shape of the temperature difference to the quiet Sun as a function of height, and not on its absolute value. Thus most 1-component models are expected to reproduce the observations at a similar level of accuracy as the Fontenla et al. models we have chosen. Secondly, in the course of the investigation we modify the facular temperature stratification in order to better reproduce the observations. Therefore, the chosen atmospheres only serve as "initial guesses". One major advantage of the Fontenla et al. models is that they form a consistent set of models, of which the quiet Sun atmosphere (FAL-C) is rather similar to the Kurucz model in its photospheric layers. Other 1-component facular models are often constructed relative to quiet-sun models that differ significantly from the Kurucz quiet-sun model, so that their use would introduce additional uncertainties into the analysis.

From a comparison of Fig. 1 with Fig. 2 it is clear that at activity maximum the temperature in the higher layers must be increased more strongly than in the lower photosphere. This condition is well fulfilled by the chosen facular models. Both have a less steep temperature drop with height in the photosphere than FAL-C (i.e. they are hotter than the quiet Sun mainly in the upper photosphere).

The flux of the active Sun predicted by our 2-component model is

$$F_{\rm a}^{\lambda} = (1-\alpha_{\rm f})F_{\rm q}^{\lambda} + \alpha_{\rm f}F_{\rm f}^{\lambda}, \quad (4)$$

where $\alpha_{\rm f}$ is the proportion of the surface occupied by faculae.

We find that model FAL-P gives too strong a wavelength dependence of $\Delta F^{\lambda}/F^{\lambda}$, but FAL-F gives approximately the correct variation in the UV, although the total flux variation is smaller than observed, and also the variation in the visible between 400 and 700 nm lies far below Lean's estimate. This wavelength range is particularly important since most of the solar flux originates there. On closer inspection, it turns out that the flux between 400 and 700 nm is produced in a very narrow height range. This is just about the height at which models F and C start to deviate. If we increase the temperature of model F slightly at the deviation point, the flux variation between 400 and 700 nm as well as the total flux variation are enhanced. The temperature stratification of the original and modified FAL-F models are shown in Fig. 3b; the resulting flux variations as a function of wavelength in Fig. 4. The $\alpha_{\rm f}$ underlying the spectrum plotted in Fig. 4 is 0.18 and the resulting total relative flux variation is 0.1%. We conclude that the new model F which differs from FAL-F by far less than the uncertainty in that model, gives a satisfactory fit to the data.

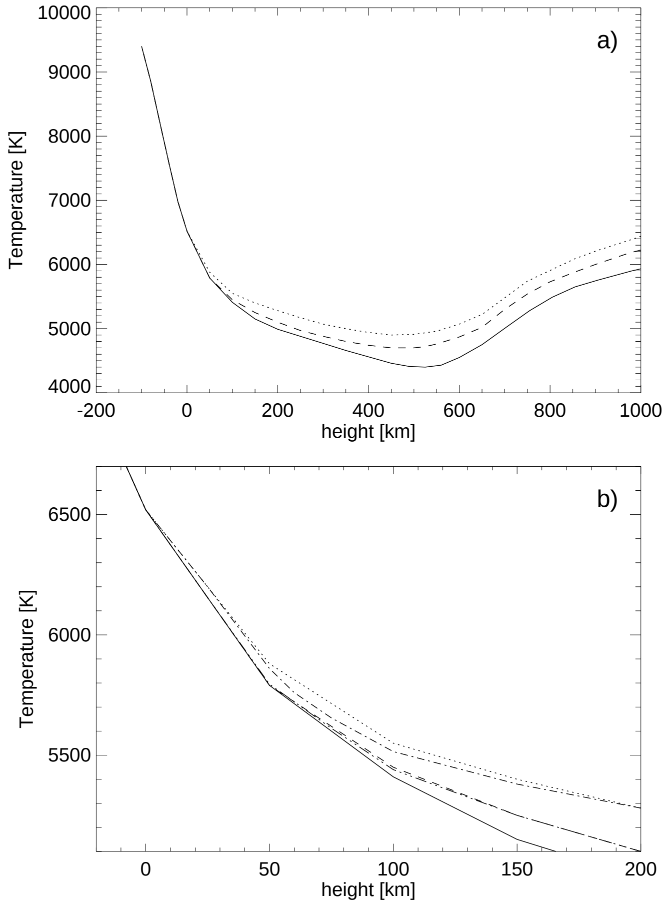

Fig. 3. a Temperature stratifications of models C (solid line), F (dashed line) and P (dotted line) of Fontenla et al. (1993, FAL). **b** Enlargement of the height range at which we altered the facular models slightly in order to obtain better fits. The line-styles of the original FAL models are as above; the altered model FAL-P is shown by the dot-dashed line, the remaining line shows the altered model FAL-F.

4. The influence of sunspots

Not only is the facular contribution to the solar spectrum larger at solar maximum, but the Sun is also more heavily spotted. Hence, although we have seen in the last section that a 2-component model can reproduce the observations relatively well, it cannot be considered to be realistic as long as the influence of sunspots is not taken into account.

We model the sunspots with a Kurucz flux spectrum corresponding to $T_{\rm eff}$ = 5250 K. This choice is driven by the following considerations. The temperature structure of umbrae (Severino et al. 1994, Rüedi et al. 1997) and penumbrae (Kjeldseth-Moe & Maltby 1969, Del Toro Iniesta et al. 1994) is close to the expectations from radiative equilibrium, i.e. it should be well described by a Kurucz model (cf. Maltby 1992 and Solanki 1997 for reviews). The effective temperature of roughly 5250 K of the typical sunspot is then given by the effective temperature of the umbra (approximately 4500 K, if both the dark and bright parts are taken into account), $T_{\rm eff}$ of the penumbra (5400–5500 K, Kjeldseth-Moe & Maltby 1969) and the ratio of umbral to penumbral area of roughly 1:3 (e.g., Steinegger et al. 1990, Solanki & Schmidt 1993), which gives approximately 5250 K. The total contrast due to the sunspot for this effective temperature is 0.3, which is close to the value used by, e.g., Foukal & Lean (1990) to model solar irradiance, and the measurements of Steinegger et al. (1990) and Chapman et al. (1994).

In addition, we initially assume that the facular contribution should be modelled using the temperature distribution of model FAL-P.

The relative flux variation as a function of wavelength in this 3-component model is given by

$$\begin{aligned}\Delta F^{\lambda}/F^{\lambda} &= [(1-\alpha_{\rm s}-\alpha_{\rm f})F_{\rm q}^{\lambda} + \alpha_{\rm s}F_{\rm s}^{\lambda} + \alpha_{\rm f}F_{\rm f}^{\lambda} - F_{\rm q}^{\lambda}]/F_{\rm q}^{\lambda} \\ &= \alpha_{\rm s}(F_{\rm s}^{\lambda}/F_{\rm q}^{\lambda} - 1) + \alpha_{\rm f}(F_{\rm f}^{\lambda}/F_{\rm q}^{\lambda} - 1)\,, \quad (5)\end{aligned}$$

where $\alpha_{\rm f}$ and $\alpha_{\rm s}$ are the facular and spot filling factors, respectively. The original FAL-P model (with the appropriate choice of $\alpha_{\rm f}$ and $\alpha_{\rm s}$) gives a good fit to the UV, but combined with our sunspot model does not give the correct $\Delta F^{t}/F^{t}$. Once more, however, only minor adjustments to the temperature stratification of FAL-P (illustrated in Fig. 3b) are required to produce good agreement.

The spectrum of the flux variations resulting from the 3-component model with modified model FAL-P is indicated by the solid line in Fig. 5 (it produces $\Delta F^{t}/F^{t} \approx 0.1\%$). The facular filling factor giving the best fit is $\alpha_{\rm f}$ = 0.04, the spot filling

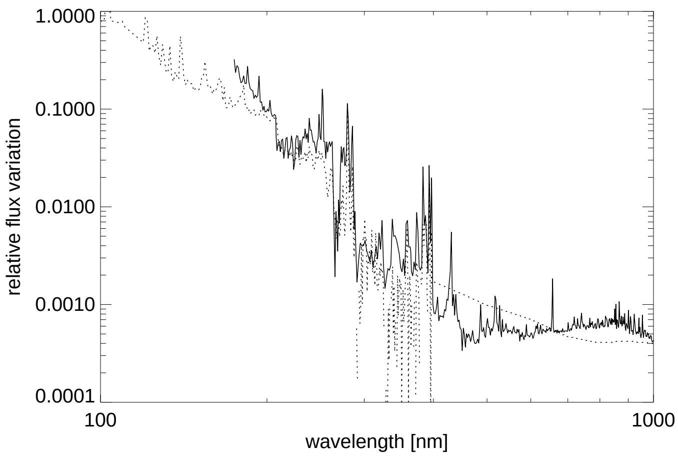

Fig. 4. Relative flux variation $\Delta F^\lambda / F^\lambda$ due to the 2-component model described in Sect. 3 (solid line), where the facular atmosphere is described by our altered model FAL-F. The dotted line is identical to that plotted in Fig. 1.

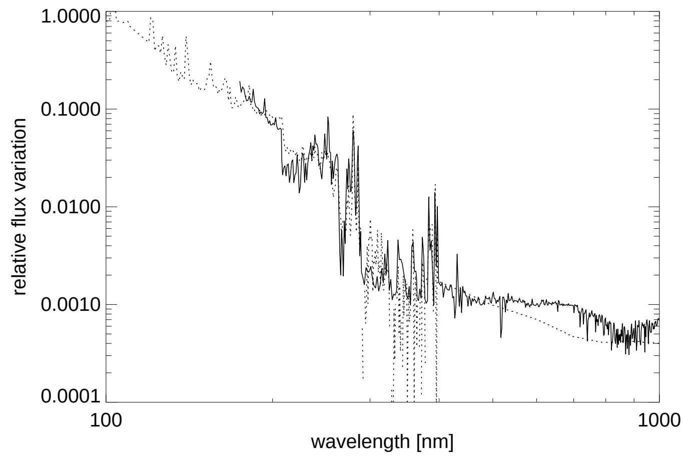

Fig. 5. Relative flux variation obtained from a 3-component model (solid line) vs. wavelength. The facular component is described by the altered FAL-P model and the facular and sunspot filling factors are 0.04 and 0.0025, respectively. The dotted line is the same as in Fig. 1

factor is α_s = 0.0025. These values depend somewhat on the choice of the spot temperature. Nevertheless, the ratio between facular and sunspot area which we find (driven by totally different considerations), namely 16, is consistent with the value of approximately 16.5 found by Chapman et al. (1997) from direct measurements. The spot area near the maxima of cycles 21 and 22 was about 0.003. Again the value we obtain lies reasonably close. We expect that by tuning the facular temperature stratification (and possibly considering umbrae and penumbrae separately) even closer agreement can be obtained.

Note that although spots have maximum contrast in the UV they have almost negligible effect at those wavelengths, because the 0.6% darkening due to spots is more than compensated for by the very large brightening due to faculae (10%). Spots only begin to affect the results at longer wavelengths when the facular contribution drops below 0.01.

The comparison between the relative flux variation due to our 3-component model and the data and estimates provided by Lean et al. (1997) are plotted in Fig. 6 over a wider spectral range than in Fig. 5. Our models differ from the *estimates* of Lean in the IR. The qualitative wavelength dependence of both models is the same, but ours show larger variability in the IR. This is partly because the FAL-P and FAL-F models do *not* incorporate the finding of Foukal et al. (1989, 1990) and Moran et al. (1992) that faculae appear dark between 1.2 and 2 μm, i.e. in the vicinity of the opacity minimum. Hence these models are too hot in the subsurface layers. The difference between the estimates persists, however, to larger wavelengths, at which the radiation comes from higher layers. At these wavelengths we expect that our model is relatively well constrained by the UV spectrum.

Our models may overestimate the brightness fluctuations in the UV (for a given temperature stratification), due to the assumption of LTE, whereas radiation from the upper photosphere often shows departures from this assumption. Thus it

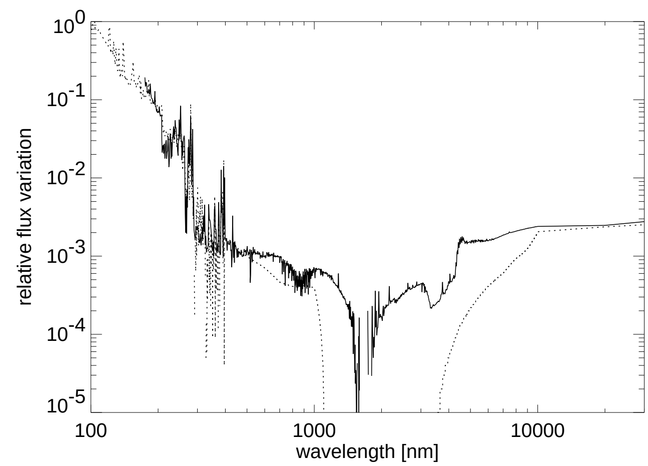

Fig. 6. The same as Fig. 5, but for a larger wavelength range

may be that the true temperature of the facular model may be even higher than we estimate.

Further uncertainty is introduced into our models by our assumption that facular and quiet-sun radiation at a given wavelength is produced at the same height. The temperature dependence of the (line and continuum) absorption coefficient generally acts to change this height somewhat when the temperature is changed. Without a full solution of the radiative transfer equation at all wavelength points for both atmospheres, it will not be possible to judge the exact influence of these height changes. Finally, the simplifications inherent in the chosen model (e.g. a single, spatially averaged temperature of faculae and of sunspots) also influence the results.

5. The contribution of different layers and wavelengths

Our models allow us to attribute to each height in the atmosphere the fraction of the total irradiance variation produced

Table 1. Relative contribution of different heights to $\Delta F^t(z)/\Delta F^t$

Height range [km]	$\Delta F^t(z)/\Delta F^t$ (2-comp)	$\Delta F^t(z)/\Delta F^t$ (3-comp)
0–100	0.83	0.89
100–200	0.12	0.07
200–300	0.02	0.02
300–400	0.03	0.02

Table 2. Relative contribution of different wavelengths to $\Delta F^t(\lambda)/\Delta F^t$ in the 3-component model.

wavelength range [nm]	$\Delta F^t(\lambda)/\Delta F^t$
200–300	0.139
300–400	0.172
400–700	0.428
700–1000	0.143
1000–2000	0.080
2000–5000	0.020
5000–10000	0.007
10000–100000	0.002

at that height. The relative contributions of 4 height bins covering the photosphere are listed in Table 1. It clearly shows that the largest contribution comes from or from just above the continuum-forming layers, but that the line-forming layers of the lower photosphere also contribute significantly. The upper photosphere only gives a small contribution. In addition to the uncertainties discussed in Sect. 4, the estimates presented in Table 1 suffer from the neglect of the chromosphere in our models (we estimate this to contribute only a few percent to the total irradiance variations, however) and from the neglect of magnetic pressure, which leads to a Wilson depression in sunspots and the small magnetic elements forming faculae. These uncertainties and the width of the contribution function to solar radiation provide the basic limitations to the height resolution that can be achieved.

Finally, in Table 2 we list the predictions of our 3-component model regarding the relative contribution of different wavelength ranges to the total irradiance variations. In the wavelength range between 200 and 400 nm, our calculations agree very well with the relative contribution as measured by Lean et al. (1997). We overestimate the contribution of larger wavelengths (beyond 1000 nm), as was already indicated in Fig. 6. This may in part be due to the fact that the facular models are too hot below τ_{500} = 1 as they neglect that faculae can appear dark around 1.6 μm. Finally, the relative contribution from the range 400–1000 nm depends sensitively on details of the temperature structure around τ_{500} = 1, which is not well constrained by the current observations.

6. Discussion and conclusions

We find good agreement between our simple models and UV observations of the spectral dependence of the relative solar irradiance (or flux) variation between solar activity maximum and minimum. The agreement with the data is particularly gratifying considering the simplicity of our approach. Since our model only incorporates the influence of faculae and sunspots (as described by relatively standard models) this good agreement suggests that the radiative properties of magnetic features on the solar surface provide the dominant contribution to irradiance variations on a solar-cycle time-scale.

Nevertheless, our analysis cannot rule out other sources of irradiance variations (e.g. subtle changes in the Sun's convective properties). This is because much of the irradiance variation is produced in the deep layers at which the facular models depart only slightly from the standard quiet-sun atmosphere. It is therefore conceivable that other processes may also introduce slight changes to these levels and produce a fraction of the change in the total irradiance.

Unfortunately it is exactly these deep layers which are particularly poorly observed, since no experiment has as yet determined the spectral irradiance in the visible over a solar cycle. The VIRGO experiment on the SOHO (Solar and Heliospheric Observatory) mission (Fröhlich et al. 1995, 1997) is thus filling an important gap and will hopefully provide us with the necessary data.

Another potential source of data on the deep layers are the observations of line variations over the solar cycle by Livingston et al. (1988), in particular the line ratios considered by Gray & Livingston (1997). In view of our results these need to be reinterpreted in terms of changes in the temperature gradient over the solar cycle rather than just a $T_{\rm eff}$ change.

On their own, our results may not provide a sufficiently strong case for a mainly surface-magnetism based cause of total irradiance variations, but taken together with the successful modelling of time series by other authors (e.g. Foukal & Lean 1986, 1988, 1990, Pap et al. 1994, Chapman et al. 1996) they do indicate that the lion's share of irradiance variations (and in particular almost all of the UV irradiance variations) are due to solar surface magnetic fields.

Our analysis confirms that practically the whole of the solar irradiance variation is produced in the lower photospheric layers and provides improved estimates of the contributions to the total irradiance variation of different heights and wavelengths.

An added bonus of our exercise is the discovery that the broad-band spectral variation of total irradiance (due to the great accuracy with which it is measured) provides a sensitive diagnostic of the temperature structure in the lower photospheric layers of faculae, in an averaged sense (i.e., neglecting the fine-scale magnetic and thermal structure, cf. e.g. Stenflo 1989, Solanki 1993). Reliable improvements to the models require observations of the spectral variations in the visible, however. Such observations are only now becoming available with the VIRGO experiment.

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