Cool Stars, Stellar Systems and the Sun
ASP Conference Series, Vol. 154, 1998
eds. R. A. Donahue and J. A. Bookbinder

The Wavelength Dependence of Solar Irradiance Variations

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Abstract:

The observed irradiance variations over a solar cycle show a strong wavelength dependence; the variations are strongest in the UV and very weak in the visible. Here we present a simple model of the spectral dependence of the solar irradiance. We can exclude models that postulate a change in the effective temperature of the Sun or of parts of the Sun. However, we find that the observed irradiance variations can be matched with a model that includes the different temperature stratification of the quiet photosphere, the faculae and the sunspots.

1. Introduction

Satellite observations taken over the last solar cycles show that the total irradiance of the Sun (the wavelength-integrated flux per unit area measured on the Earth) not only varies as a function of time, but that it also shows a large spectral variation, with strong changes in the UV flux and much weaker variations in the visible.

To model the temporal variations, it is usually assumed that the variations are due to the change in the amount and concentration of magnetic flux on the solar surface (see e.g., Foukal & Lean 1990; Pap et al. 1994). The changing magnetic flux is then divided into components that represent the radiation from dark sunspots and from bright facular regions. Here we follow this approach to model the height variation of the temperature of the quiet and the active Sun with a view to determining the spectral variation of the solar irradiance and shedding light on the role of surface magnetism.

2. The Model

Our initial tests showed that it is impossible to produce large enough UV-variations if one assumes that the change in the irradiance is solely due to a temperature increase of the Sun (Solanki & Unruh 1998, see also Fig. 1). We therefore conclude that the change in temperature of the solar atmosphere between activity maximum and minimum *must be height dependent.* Here, we consider a 3-component model of which one component is the quiet Sun, another

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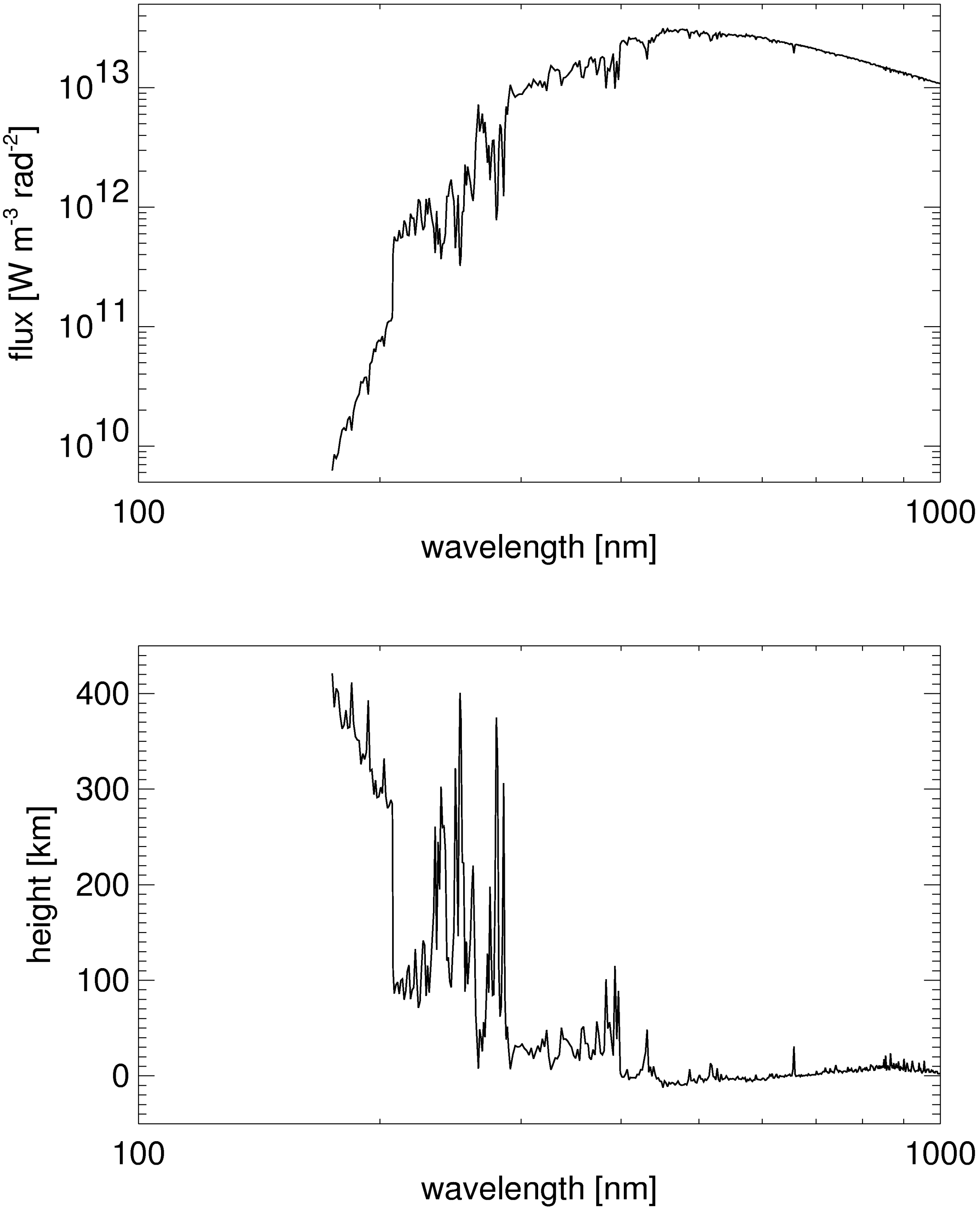

Figure 1. *(top panel)*: Flux spectrum F_{q}^{λ} resulting from the quiet-sun model of Kurucz (1991). *(bottom panel)*: Formation height of the "black-body" flux as a function of wavelength. This is obtained by calculating the black-body temperature (using Planck's function) at each wavelength point from the flux shown above. The temperature is then translated into a height using FAL-C (see Fig. 2).

is a bright facular component that is allowed to have a different temperature gradient from the quiet Sun and the third component represents sunspots.

As the basic flux spectrum for the quiet Sun, we use Kurucz's solar model with $T_{\mathrm{eff}} = 5777$ K (Kurucz 1991, 1992). The quiet-Sun temperature stratification is taken from model C of Fontenla et al. (1993), FAL-C; the facular atmosphere is represented by their model P, FAL-P; and the sunspots are calculated using Kurucz's radiative equilibrium model with T_{eff}=5250 K, which is about the average T_{eff} of sunspot umbrae and penumbrae[5]. The flux spectrum of the quiet Sun and the height at which the flux is formed at each wavelength is shown in Fig. 1; the temperature stratification of the models is shown in Fig. 2.

In the three-component model, the relative flux variation as a function of wavelength, $(F_{\mathrm{a}}^{\lambda} - F_{\mathrm{q}}^{\lambda})/F_{\mathrm{a}}^{\lambda}$, is given by

$$\Delta F^{\lambda}/F^{\lambda} = \left[(1-\alpha_{\mathrm{s}}-\alpha_{\mathrm{f}})F_{\mathrm{q}}^{\lambda} + \alpha_{\mathrm{s}}F_{\mathrm{s}}^{\lambda} + \alpha_{\mathrm{f}}F_{\mathrm{f}}^{\lambda} - F_{\mathrm{q}}^{\lambda}\right]/F_{\mathrm{q}}^{\lambda}.$$

F_{q} and F_{a} denote the quiet-Sun and the active-Sun flux; F_{s} and F_{f} are the spot and the facular flux and α_{s} and α_{f} are the spot and the facular filling factors. The spectrum of the flux variations resulting from this 3-component model with our modified FAL-P model is indicated by the solid line in Fig. 3. Also plotted are the data by Lean (1991) and Lean et al. (1997) who have compiled the observed solar irradiance variability in the UV and estimated the variability at longer wavelengths during solar cycle 21. The small modifications to model P (as shown in Fig. 2b) were necessary to obtain a better fit in the visible and to achieve $\Delta F^{t}/F^{t} \approx 0.1\%$ in agreement with the ACRIM observations (Willson & Hudson 1991).

The facular filling factor giving the best fit is $\alpha_{\mathrm{f}} = 0.04$, the spot filling factor is $\alpha_{\mathrm{s}} = 0.0025$. 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. Similarly, our value for the spot filling factor lies reasonably close to the observed value of 0.003 near the sunspot maxima in cycles 21 and 22.

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

Height range [km]	$\Delta F^{t}(z)/\Delta F^{t}$
0–100	89 %
100–200	7 %
200–300	2 %
300–400	2 %

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[5] This assumes umbral and penumbral temperatures of about 4500 K and 5500 K respectively and an umbral-to-penumbral ratio of 1:3

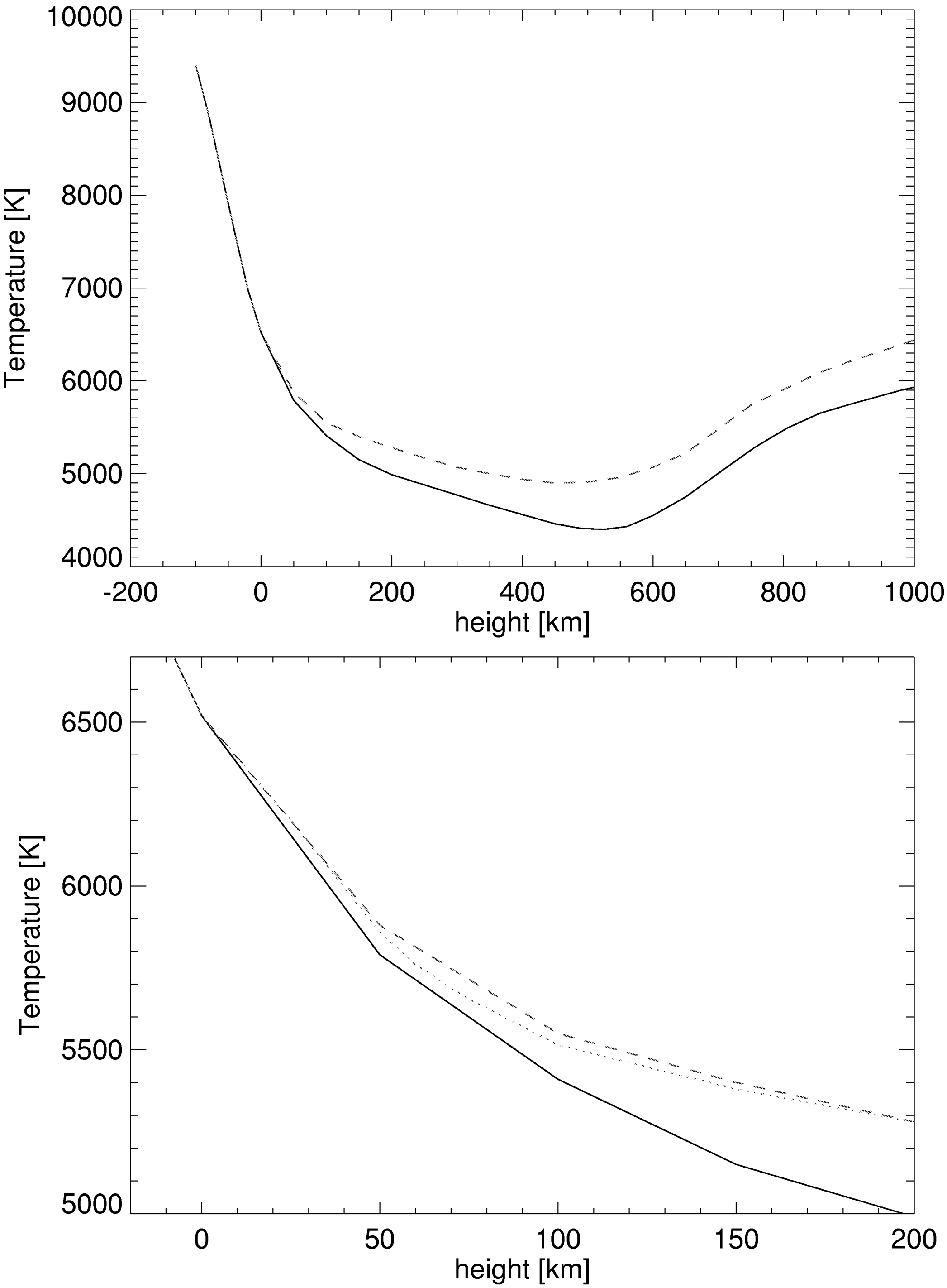

Figure 2. *(top panel)*: Temperature stratifications of models C (black solid line) and P (red dashed line) of Fontenla et al. (1993). *(bottom panel)*: Enlargement of the height range at which we altered the facular model slightly in order to obtain better fits. The line-styles of the original FAL models are as above; the altered model FAL-P is shown by the orange dotted line.

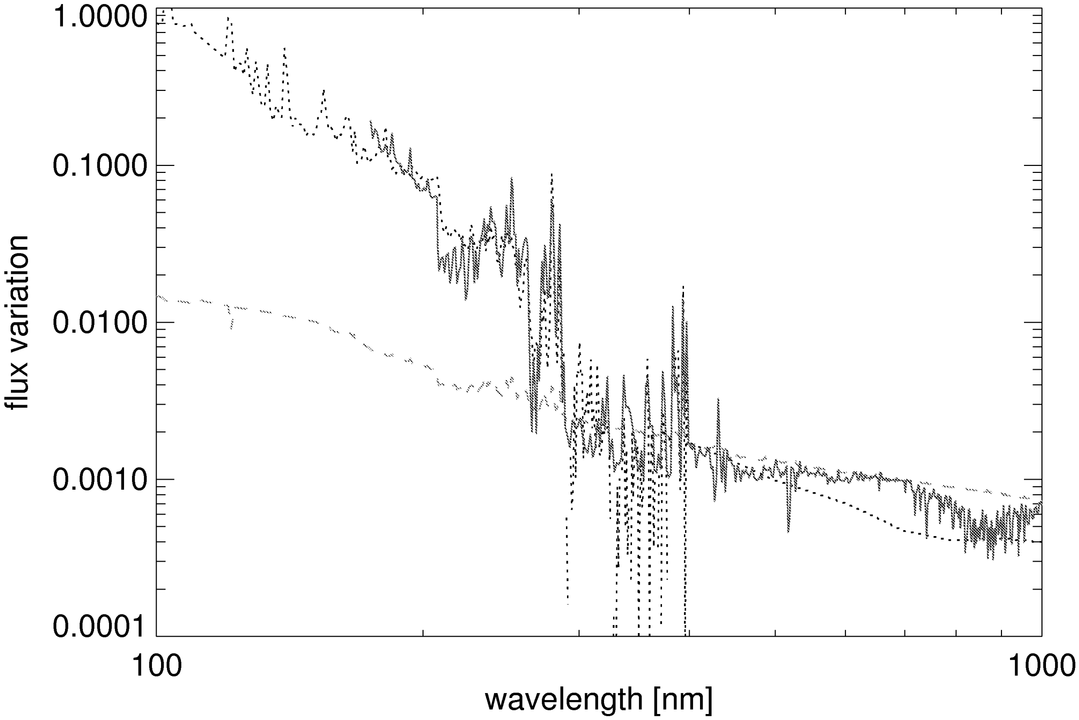

Figure 3. The solid line shows the relative flux variation, $(F_{\rm a}^{\lambda} - F_{\rm q}^{\lambda})/F_{\rm a}^{\lambda}$, obtained from the 3-component model as a function of wavelength. ($F_{\rm a}^{\lambda}$ and $F_{\rm q}^{\lambda}$ are the flux at activity maximum and activity minimum respectively.) The facular component is described by the altered FAL-P model (see Fig. 2b) and the spot component is described by the flux spectrum of the Kurucz model at 5250 K. The facular and sunspot filling factors are 0.04 and 0.0025 respectively. The dotted line shows the irradiance variations as compiled by Lean et al. (1997). Note that the values for $\lambda > 400$ nm are estimates. The thin dashed line shows the irradiance variations if the solar temperature is increased by 1.5 K, i.e. when we assume that there is no height-dependent temperature change between the facular and the quiet-Sun regions.

3. The Contribution of Different Layers and Wavelengths

Using our model, we can calculate the height at which the irradiance variations are produced in the atmosphere. The relative contributions of 4 height bins covering the photosphere are listed in Table 1. It clearly shows that the largest contribution comes from within or from just above the continuum-forming layers, but that the line-forming layers of the lower photosphere also contribute significantly. The upper photosphere gives only a small contribution.

Table 2 lists the predictions of our 3-component model regarding the relative contribution of different wavelength ranges to the total irradiance variations and compares them to measurements (200–400 nm) and estimates by Lean et al. (1997). The values in the visible agree very well; for wavelengths above

Table 2. Relative contribution of different wavelengths to $\Delta F^t(\lambda)/\Delta F^t$.

wavelength range [nm]	$\Delta F^t(\lambda)/\Delta F^t$ our model	$\Delta F^t(\lambda)/\Delta F^t$ Lean (priv comm)
200–300	14 %	13 %
300–400	17 %	18 %
400–700	43 %	(42 %)
700–1000	14 %	(12 %)
1000–2000	8 %	(–4 %)
2000–5000	2 %	(–1 %)

1000 nm our calculated relative contribution is much larger than Lean's estimate. Part of this is because we do not take into account that faculae appear dark at 1.65 μm (see e.g., Moran et al. 1992).

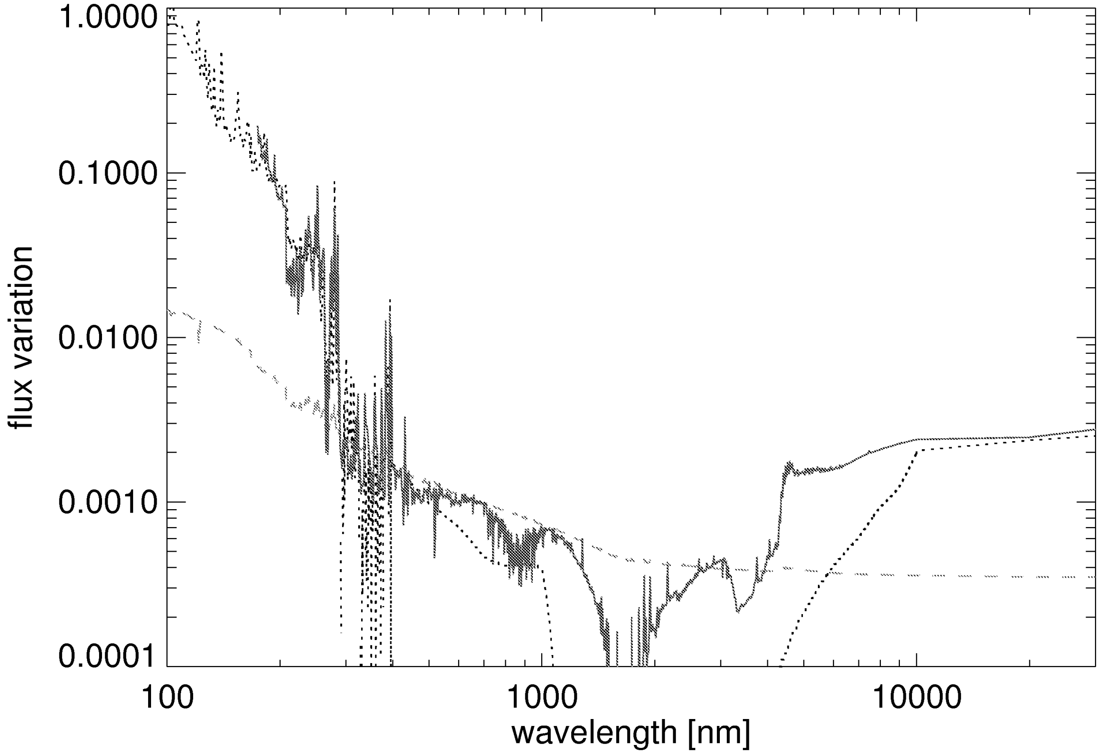

Figure 4. The relative flux variation between solar maximum and minimum between 100 nm and 30 μm. As in Fig. 3 the dotted line is the estimate by Lean et al. 1997, the solid line shows our calculations for a 3-component model, and the dashed line shows the variation for a global temperature increase.

4. 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. Considering the simplicity of our approach, the agreement with the data is particularly gratifying. Since our model only incorporates the influence of faculae and sunspots (as described by relatively standard models) the 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. Furthermore, our analysis confirms that practically the whole of the solar irradiance variation is produced in the lower photospheric layers.

Acknowledgments. Dr. J. Lean kindly provided us with her compilation of the observational data, which we gratefully acknowledge. We also thank H. Hudson for helpful comments. YCU would like to acknowledge support through a PPARC-funded PDRA as well as support through grant No. 7302 of the Austrian Fond zur Förderung der wissenschaftlichen Forschung.

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