# MODELLING SOLAR IRRADIANCE VARIATIONS: COMPARISON WITH OBSERVATIONS, INCLUDING LINE-RATIO VARIATIONS

Y. C. UNRUH (`unruh@astro.univie.ac.at`)
*Institute of Astronomy, University of Vienna, Türkenschanzstr. 17, 1180 Wien, Austria*

S. K. SOLANKI (`solanki@linmpi.mpg.de`)
*Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany*

M. FLIGGE (`fligge@astro.phys.ethz.ch`)
*Institute of Astronomy, ETH Zentrum, CH-8092 Zürich, Switzerland*

Received: 22 October 1999; Accepted in final form: 27 January 2000

**Abstract.** Solar irradiance variations show a strong temporal and spectral dependence. The progression of the Sun through its activity cycle as well as solar rotation are mirrored in the irradiance variations. The spectral dependence is such that the variations are several magnitudes larger in the EUV than in the visible or infrared.

We present a simple 3-component model that is based on the assumption that changes in the solar flux are exclusively due to changes in spot and facular coverage. We compare our model to observations of the spectral solar irradiance variations. Despite its simplicity, we find that the agreement between our model and the observations is surprisingly good. We also explore the reliability and the limitations of our approach by comparing observations of the solar facular contrast and of the changes in spectral line depths with our calculations.

## 1. Introduction

Models of total and spectral irradiance variations are important not just for obtaining an understanding of the physical causes of solar irradiance variations, but also for successful reconstructions of such variations for times prior to satellite measurements. We summarize the main results of a simple model, emphasizing the comparison of its predictions with a wide variety of observations. In particular we present the first comparison with the variation of selected line ratios over the solar cycle (Sect. 4.3).

## 2. The Model

To model the solar irradiance variations, we assume that they are solely due to changes in the spot and facular coverage (Solanki and Unruh, 1998). The facular component here includes any brightenings due to magnetic features, i.e. also the network. The flux of the active Sun is then simply the sum of the three components

*Space Science Reviews* **94:** 145–152, 2000.

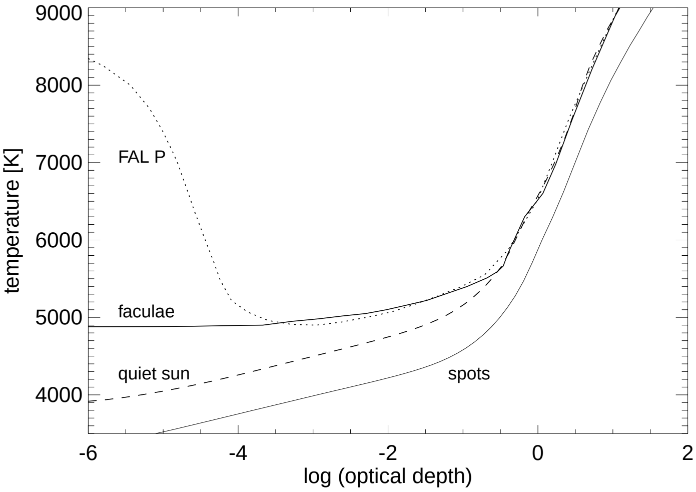

*Figure 1.* The temperature stratification of the quiet-sun (dashed line), the facular (upper thick solid line) and the spot model (thin solid line) atmospheres as a function of optical depth. The dotted line shows the original facular model by Fontenla et al. (1993).

(quiet-Sun, spots and faculae) weighted according to their filling factors:

$$F_\lambda = (1 - f_F - f_S)F_\lambda^\odot + f_F F_\lambda^F + f_S F_\lambda^S,$$

where $f_F$ and $f_S$ are the facular and the spot filling factors respectively. The filling factors here are defined to be the fraction of the projected solar disk covered by spots or faculae. $F_\lambda$, $F_\lambda^\odot$, $F_\lambda^F$ and $F_\lambda^S$ are the active-sun, the quiet-sun, the facular and the spot fluxes.

The fluxes are calculated with the ATLAS9 spectral synthesis code written by R. Kurucz that takes into account up to 58 million lines by means of opacity distribution functions. We neglect any non-LTE effects in our calculations. For the quiet-Sun flux we use Kurucz's solar model atmosphere (Kurucz, 1991). This describes a quiet photosphere in radiative equilibrium with an effective temperature of 5777 K. For the sunspot radiative flux we use a model atmosphere with an effective temperature of 5150 K that was interpolated from the Kurucz grid of model atmospheres. This model represents the joint contribution of the umbral and penumbral flux, assuming a ratio of almost 1:3 for the umbral and penumbral areas. We assumed temperatures of approximately 4500 K and 5400 K for sunspot umbrae and penumbrae respectively (see Solanki and Unruh, 1998, and Fligge et al., 1998). The facular model atmosphere was developed from model P of Fontenla et al. (1993) which we used as a starting point. We excluded the temperature inversion in the upper photosphere, thereby creating a “pseudo-LTE” atmosphere. Further changes were introduced to achieve better agreement with the observations. The model atmospheres of the three components are shown in Fig. 1 along with model P of Fontenla et al. (1993). For more details see Unruh et al. (1999).

Note that ATLAS9 also allows us to calculate the intensities (as a function of limb angle) for all three components. We can hence obtain the total flux via a disk integration over all surface pixels (Fligge et al., 2000a, 2000b) and we can also calculate the limb-dependent contrasts of the faculae (see Sect. 4.2).

## 3. Comparison with Observations: Spectral Irradiance Variations

The total irradiance variation over one solar cycle is on the order of 0.1 % (Willson and Hudson, 1991; Fröhlich and Lean, 1998). The variations are small in the visible and IR, but the solar flux can vary by more than 100 % in the EUV. The spectral dependence of the irradiance variations over a solar cycle has been compiled by Lean (1997) and is plotted in Fig. 2 (dotted line). Note that the data in the UV are measurements, while the behaviour in the visible and IR has largely been estimated.

We obtain the facular and spot filling factors from a fit to the data from Fig. 2 over the wavelength range between 200 and 400 nm. We also require the “total” irradiance variations (integrated from 164 to 100 000 nm) to amount to 0.1 %. Our fit matches the overall behaviour of the data well, although there are differences in detail. We tend to overestimate the variability between about 320 and 380 nm. Part of this is due to the greater sensitivity of the fit to the larger variations between 200 and 260 nm, though we also expect discrepancies at UV wavelengths due to the LTE approach (see Fontenla et al., 1999 and White et al., 1999 for the description of a non-LTE approach). Some of the difference may also arise because the measurements in the range from 300 to 400 nm are associated with relatively large errors.

In order to check whether a facular component with a distinct temperature gradient was really needed to reproduce the data, we also calculated the irradiance variations that one would obtain if the Sun were 1 K hotter at activity maximum compared to activity minimum. These irradiance variations are shown by the dashed lines in Fig. 2. They clearly do not reproduce the spectral dependence of the irradiance and underestimate the variations in the blue part of the spectrum by a large amount while overestimating the variability in the visible and IR. The temporal variation of the total and the spectral variation predicted by our model has been worked out and compared with ACRIM (Willson and Hudson, 1991) and VIRGO (Fröhlich et al., 1997) data by Fligge et al. (1998; 2000a; 2000b). For details we refer the reader to those papers.

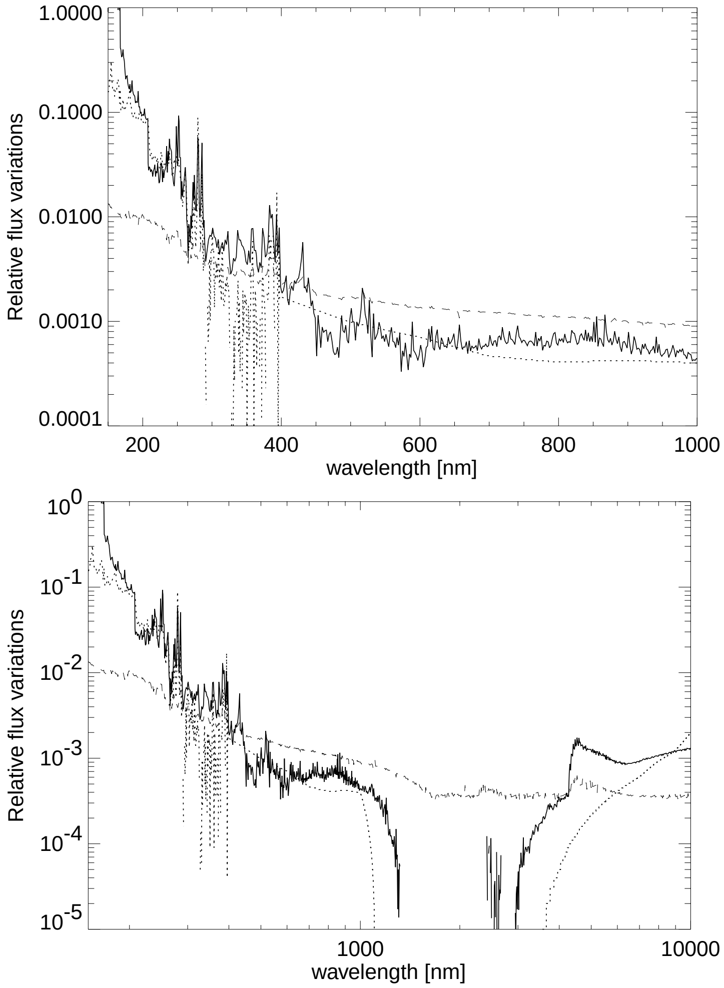

*Figure 2.* Relative solar irradiance variation in the wavelength ranges between 150 and 1000 nm (top) and between 150 and 10 000 nm (bottom). Plotted is the relative difference between the solar spectrum at activity maximum and minimum. The data compiled by Lean (1997) as well as her estimates are represented by the dotted lines; the solid lines show our model with a facular filling factor of 2.7 % and a spot filling factor of 0.23 %. The predictions of a model whereby the temperature of the Sun at solar maximum has been raised by 1 K relative to activity minimum are indicated by the dashed lines.

## 4. Comparison with Observations: Further Consistency Checks

### 4.1. SPOT AND FACULAR COVERAGE

We can check whether the spot and facular filling factors that we obtain are in line with the observed values. Near the maxima of cycles 21 and 22, spots covered about 0.2 % of the solar surface. From observations spanning a 7.5 year-period during cycle 22, Chapman et al. (1997) found the ratio of facular to spot area to be 16.7, although the values varied considerably over the solar cycle.

In order to match the observations plotted in Fig. 2 we need facular filling factors of the order of 2 % to 3 %. The spot filling factor required depends on the facular filling factor that is adopted and ranges from 0.1 % to almost 0.3 %. The corresponding ratios of facular to spot filling factor then range from 20 down to 12 for the lowest and highest filling factors respectively. Our spot and facular filling factors are thus in good agreement with the observations.

### 4.2. FACULAR CONTRASTS

We have calculated the contrasts of the faculae as a function of limb angle and compared them to solar measurements. The contrast is defined as $(I_f - I_q)/I_q$, where $I_f$ and $I_q$ are the intensity of the faculae and the quiet Sun. The spread between different contrast measurements is very large, reflecting the differences in facular structure, wavelength of the observations, magnetic filling factor and size. The scatter in the measurements is evident in Fig. 3, where the linked symbols represent a selection of measurements. The situation is particularly ambiguous close to the solar limb where the measurements by e.g. Libbrecht and Kuhn (1985) indicate a decrease in the contrast beyond about $\mu = 0.2$. Our model is plane-parallel and neglects facular fine structure. We therefore do not expect our calculations to be accurate close to the limb. As the relative effect of the areas close to the limb is small, this should not produce large discrepancies in our irradiance calculations. The three thick lines (solid, dashed and dotted) show our calculations. Given the fact that the observations are inconsistent with each other, our model gives reasonable results (for a more detailed discussion see Unruh et al., 1999).

Our model exhibits excellent agreement with the spectral behaviour of the facular contrast measured by Chapman and McGuire (1977), as shown in Fig. 4. Unruh et al. (1999) also showed that with the same set of free parameters the model gives changes in line blanketing between activity minimum and maximum that are consistent with the findings of Mitchell and Livingston (1991).

### 4.3. CHANGES IN LINE RATIOS

As the Sun moves through its cycle, changes in line strengths can be observed in most absorption lines. By considering the ratios between the depths of different lines, Gray and Livingston (1997a) were able to neutralise many of the uncertainties in the measurements. They found the C I (538.03 nm) to Fe I (537.96 nm) ratio ($r_{\mathrm{Fe}}$) to vary by about 0.004 and the C I (538.03 nm) to Ti II (538.13 nm) ratio ($r_{\mathrm{Ti}}$) to vary by 0.003 between solar activity minimum and maximum. These variations amount to about 1 % of the line ratios. After an empirical temperature calibration of the line ratio changes, based on a comparison with stellar observations (Gray and Livingston, 1997b) they interpreted these variations to be due to a 1.5 K temperature rise of the Sun from activity minimum to maximum. They did

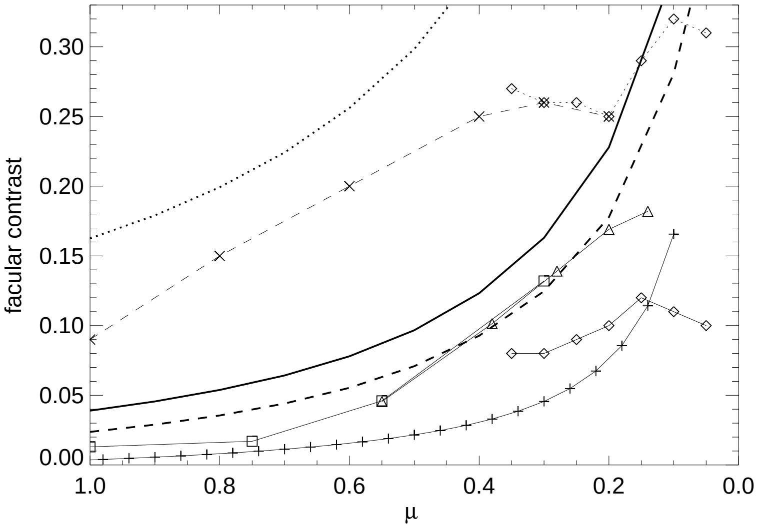

*Figure 3.* Selected facular contrast measurements, as well as contrasts calculated using our model, plotted vs. limb angle. The squares, crosses, diamonds and triangles indicate data obtained by Frazier (1971), Auffret and Muller (1991) (at 575 nm), Wang and Zirin (1987) (at 386 nm and 525 nm) and Taylor et al. (1998) respectively. The curve linking the plus signs is the parameterisation adopted by Lawrence et al. (1988). Unfortunately the information at what wavelengths the contrasts were measured was not always available. In these cases we assumed that the data were taken around 525 nm. Solid lines link data taken at about 525 nm, dotted lines data below 400 nm and dashed lines data at about 575 nm. The thick curves show our calculations for filters centred at 386 nm (dotted line), 525 nm (solid line) and 575 nm (dashed line). Above about 500 nm the filter width is relatively unimportant. This is not the case in the blue, where e.g. a reduction in the passband from 50 nm to 10 nm predicts an increase in contrast by almost a factor of two.

not consider the influence of changes in the temperature gradient over the cycle, or of the fact that these changes may be concentrated in a small fraction of the solar surface (since they are expected to be associated with the magnetic field).

We have calculated the changes in the line ratios between solar minimum and maximum for our three-component model and for a model where the temperature has been raised by 1.5 K at solar maximum (i.e. similar to Gray and Livingston's model, but based on radiative transfer calculations). Our preliminary findings are summarized in the following table.

| change in line ratio | 3-component model | $\Delta T$ model | Gray and Livingston (data) |
|---|---|---|---|
| $\Delta r_{\mathrm{Fe}}$ | 0.0018 | 0.0008 | 0.004 |
| $\Delta r_{\mathrm{Ti}}$ | 0.0015 | 0.0006 | 0.003 |

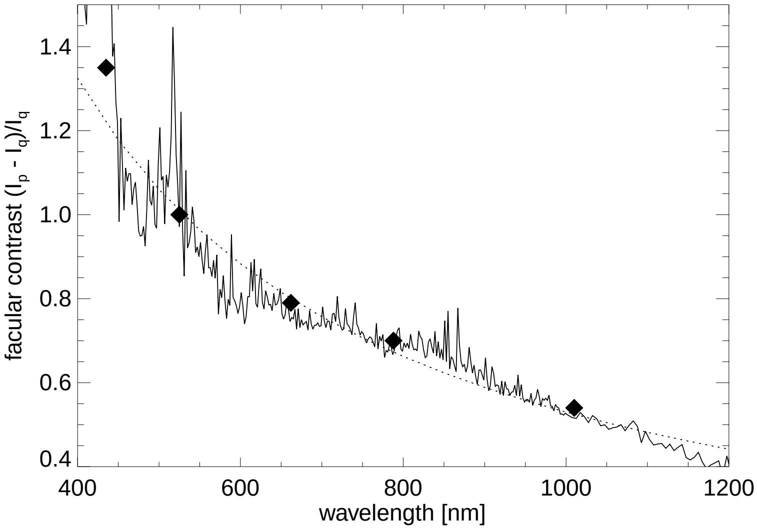

*Figure 4.* The behaviour of the facular contrast with limb angle as measured by Chapman and McGuire (1977): diamonds. The solid line is the facular contrast obtained with our model. The contrasts have been normalised to be unity at 530 nm. The dotted line shows the inverse wavelength fit suggested by Chapman and McGuire (1977).

Neither of the models is able to satisfactorily reproduce the data. However, our 3-component model yields stronger line-ratio variations than a simple temperature increase, though they are still about a factor of two lower than the measurements. The cause of the discrepancy is still unclear. It may be due to the uncertainties associated with our calculations, not least because of uncertainties in the model atmospheres. For instance, we find that line ratios calculated from the quiet-sun model and from the standard Kurucz model atmospheres for stars between 5500 and 6000 K cannot be reconciled with the observations of solar-type stars in this temperature range by Gray and Livingston (1997b). This poor correspondence may, however, also partly have to do with the simple empirical calibration used by them. For example, we find that the line ratios also depend on gravitational acceleration and not just temperature.

## 5. Conclusions and Outlook

- The 3-component model matches the measured spectral irradiance variations reasonably well. It can be used to calculate the solar irradiance from solar disk images in a straightforward way. The model also reproduces a number of further observational constraints.
- Some discrepancies remain in the blue, and particularly between 300 and 400 nm. The UV calculations should improve when non-LTE calculations are performed.

- We have presented a preliminary comparison with the cyclic line-ratio variations published by Gray and Livingston (1997a; 1997b). Although our model fares better than a simple increase of the effective temperature, it still does not give a satisfactory fit to the the data.
- Improvements to the model which take into account that quiet-region and active region faculae have distinct temperature stratifications are planned.

## Acknowledgements

J. Lean kindly provided us with her compilation of the observational data, which we gratefully acknowledge. YCU would like to acknowledge support from the Austrian Fond zur Förderung der wissenschaftlichen Forschung under grant No. 7302. MF acknowledges support from the Swiss Nationalfonds under grant No. 2000-046894.96.

## References

Auffret, H. and Muller, R.: 1991, *A&A* **246**, 264.
Chapman, G. A. and McGuire, T. E.: 1977, *ApJ* **217**, 657.
Chapman, G. A., Cookson, A. M. and Dobias, J. J.: 1997, *ApJ* **482**, 541.
Fligge, M., Solanki, S. K., Unruh, Y. C., Fröhlich, C. and Wehrli, C.: 1998, *A&A* **335**, 709.
Fligge, M., Solanki, S. K. and Unruh, Y. C.: 2000a, *A&A* **353**, 380.
Fligge, M., Solanki, S. K. and Unruh, Y. C.: 2000b, *Space Sci. Rev.*, this volume.
Fontenla, J. M., Avrett, E. H. and Loeser, R.: 1993, *ApJ* **406**, 319.
Fontenla, J. M., White, O.R., Fox, P.A., Avrett, E. H. and Kurucz, R.L.: 1999, *ApJ* **518**, 480.
Frazier, E. N.: 1971, *Solar Phys.* **21**, 42.
Fröhlich, C. and Lean, J.: 1998, *GRL* **25**, 4377.
Fröhlich, C. et al.: 1997, *Solar Phys.* **170**, 1.
Gray, D. F. and Livingston, W. C.: 1997a, *ApJ* **474**, 802.
Gray, D. F. and Livingston, W. C.: 1997b, *ApJ* **474**, 798.
Kurucz, R. L.: 1991, in Stellar Atmospheres: Beyond Classical Models, L. Crivellari, I. Hubeny, D. G. Hummer (Eds), Kluwer, Dordrecht, p. 441.
Lawrence, J. K. and Chapman, G. A.: 1988, *ApJ* **335**, 996.
Lean, J.: 1997, *ARA&A* **35**, 33.
Libbrecht, K. G. and Kuhn, J. R.: 1985, *ApJ* **299**, 1047.
Mitchell, W. E. Jr. and Livingston, W. C.: 1991, *ApJ* **372**, 336.
Solanki, S. K. and Unruh, Y. C.: 1998, *A&A* **329**, 747.
Taylor, S. F., Varsik, J. R., Woodard, M. F. and Libbrecht, K. G.: 1998, *Solar Phys.* **178**, 1.
Unruh, Y. C., Solanki, S. K. and Fligge, M.: 1999, *A&A* **345**, 635.
Wang, H. and Zirin, H.: 1987, *Solar Phys.* **110**, 281.
White, O.R., Fontenla, J. M. and Fox, P.A.: 2000, *Space Sci. Rev.*, this volume.
Willson, R. C. and Hudson, H. S.: 1991, *Nat* **351**, 42.

*Address for Offprints:* S. K. Solanki, Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany