The influence of an inclined rotation axis on solar irradiance variations

R. Knaack[1], M. Fligge[1], S.K. Solanki[1,2], Y.C. Unruh[3]

[1] Institute of Astronomy, ETH Zentrum, CH-8092 Zürich, Switzerland
[2] Max-Planck Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany
[3] Institute of Astronomy, University of Vienna, Türkenschanzstr. 17, A-1180 Vienna, Austria

Abstract. The irradiance variations of the Sun over the solar cycle are relatively small compared with sun-like stars (Radick et al., 1998). It has been proposed that a random distribution of stellar rotation axes relative to the ecliptic plane could explain their larger variability (Schatten, 1993). We examine the influence on total irradiance variations of the inclination of the solar rotation axis relative to an observer. A three-component model is used to calculate the relative flux variations of a given distribution of active regions on the surface of the Sun as a function of the inclination. One component is the quiet Sun, another is a sunspot component and the third describes the faculae. We find that the inclination effect increases the total irradiance variations of the Sun maximally by 40%. The most probable value is approximately 5%. This is much less than former studies (Schatten, 1993, Radick et al., 1998) suggested.

1. Introduction

The total irradiance of the Sun exhibits a prominent eleven-year cycle, which is correlated to the sunspot cycle. The cyclic variation of solar total irradiance, which has an amplitude of about 0.1% (Fröhlich & Lean, 1998), is caused by the small imbalance between the excess flux of faculae and the flux deficit of sunspots (Foukal & Lean, 1998). Compared with sun-like stars, the long-term photometric variations of the Sun are subdued by a factor of 2–3 (Lockwood et al., 1992, Radick et al., 1998). One possible explanation [Schatten 1993] might be the special position of a terrestrial observer which confines solar active regions to low and intermediate latitudes. An observer high above the ecliptic plane, however, would see a different distribution of sunspots and faculae, i.e. the active regions would appear closer to the limb, as is shown in Figure 1 for two zonal bands. This affects the observed solar irradiance and its variations, mainly because white-light faculae are better seen at the limb than at disk centre whereas the Wilson depression reduces the visibility of sunspots near the limb. Altogether, an increase of the total irradiance variation is expected when viewing the Sun out of the equatorial plane. Taking into account a random distribution of stellar rotation axes relative to the ecliptic plane, this inclination effect should enhance the apparent variability of sun-like stars.

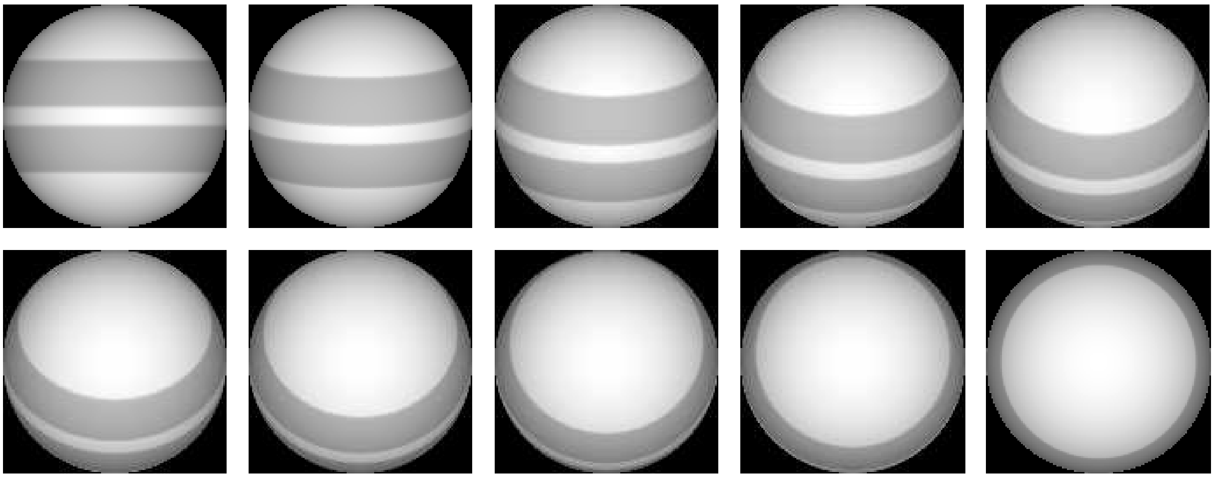

Figure 1: The geometric effect of a rotation axis tilted relative to the observer for two zonal latitude bands between $\pm 5°$ and $\pm 30°$. The inclination i decreases in steps of $10°$ from the upper left ($i = 90°$) to the lower right ($i = 0°$).

In order to calculate the relative flux variations caused by active regions as a function of inclination, the intensity as a function of limb angle has to be known for the faculae, sunspots and the quiet Sun. For this purpose we use a three component model according to Unruh et al. [1999], which is introduced in the next section and was originally proposed by Solanki & Unruh [1998].

2. The model

The model consists of three components, namely quiet-sun, faculae and spots. In order to calculate intensities and limb-dependent contrasts for each of these components under the assumption of LTE, Kurucz's ATLAS9 program was applied (Kurucz, 1992, Castelli & Kurucz, 1994). The quiet-sun intensities were obtained by Kurucz's solar model atmosphere with $T_{\text{eff}} = 5777$ K. The spot intensities (averaged over umbra and penumbra) were calculated from a model atmosphere of 5150 K which in turn was interpolated from the Kurucz grid of model atmospheres. This temperature corresponds to a ratio of umbral to penumbral area of approximately 1:3.

Model P of Fontenla et al. [1993] was used as a starting point for the facular model. Slightly modified, this model was remarkably successful in fitting the spectral irradiance variations and also data obtained by VIRGO (see Unruh et al. 1999 and Fligge et al. 1999 for details).

In principle, this model allows us to calculate the inclination effect for any wavelength range between 160 nm and 160'000 nm. In this publication, however, only the total wavelength range is considered. The resulting contrasts C for spots and faculae are shown in Figure 2 as a function of $\mu = \cos\theta$, with θ being the heliographic angle between the observer and the normal to the Sun's surface. The contrast is defined by

$$C_{\mu,\Lambda} = \frac{\int_\Lambda I_\mu(\lambda)\, d\lambda}{\int_\Lambda I_\mu^{qs}(\lambda)\, d\lambda} - 1 \qquad \mu \in [0,1],\ \lambda \in \Lambda\,, \tag{1}$$

where the integration runs over the total wavelength range Λ. I_μ denotes the intensity spectra of spots or faculae, I_μ^{qs} stands for the intensity spectrum of the quiet Sun. Obviously the spot contrast remains practically constant, if foreshortening effects like the Wilson depression are neglected.

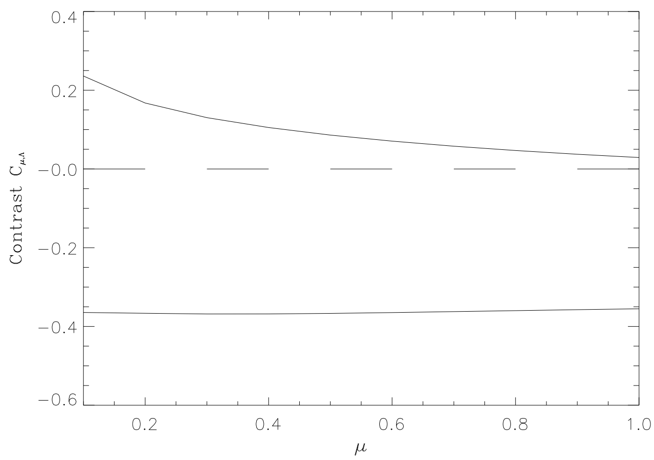

Figure 2: Facular contrast ($C_{\mu,\Lambda} > 0$) and spot contrast ($C_{\mu,\Lambda} < 0$) vs. μ for the total wavelength range $\Lambda = [160\,\mathrm{nm}, 160'000\,\mathrm{nm}]$.

3. The inclination effect

We modified a Doppler imaging code written by A. Collier Cameron (see e.g. Collier Cameron 1997), to calculate the relative flux variations of a given distribution of faculae and spots on the surface of the Sun as a function of the inclination i. For this purpose, we placed in each hemisphere a facular and a sunspot belt, each totally smeared in latitude. This approximation neglects short-term variations due to the rotation of the Sun. The facular and sunspot belts were then filled with a certain percentage of faculae and spots, thereby fixing the total facular and spot coverage, A_f and A_s, respectively. Denoting the fluxes of the quiet Sun, the sunspots and the faculae with F_{qs}, F_s and F_f, the relative flux variation becomes

$$\frac{\Delta F}{F} \equiv \frac{F_{tot} - F_{qs}}{F_{qs}} = \frac{F_s + F_f}{F_{qs}}\,, \tag{2}$$

where $F_{tot} = F_{qs} + F_s + F_f$ is the sum over all three components.

We first tried to reproduce the inclination effect as predicted by Schatten [1993] or Radick [1998] to test our program. The results are shown in the next two subsections.

3.1. Schatten's prediction

Schatten [1993] used the active-region model of Sofia et al. [1982], where the limb-darkening and the contrast of faculae and sunspots are described by polynomials of second degree. The coefficients for the contrast functions were obtained by least square fits to the ACRIM data in the early 1980s. To investigate the inclination effect, Schatten placed groups of small individual faculae and spots within two bands ranging from 10° to 40° on each hemisphere. The areas were adjusted to provide a cyclic variation of about 0.18%, which is about twice as much as the value of 0.1% suggested by Fröhlich and Lean [1998]. The facular-to-spot flux ratio was fixed to about 5:4. The influence of the inclination on the relative flux variation obtained by Schatten is shown on the upper left diagram of Figure 3. We define here the inclination i as the angle between the solar rotation axis and the line-of-sight. The relative flux variation $\Delta F/F$ (bold line) starts at 0.18% ($i = 90°$) and increases up to 1.1% ($i = 30°$), i.e. a factor of 6 higher, followed by a pronounced decline. The statistically most probable value for the increase, corresponding to an inclination of approximately 57° (Radick et al., 1998), is a factor of about 3. The dotted line shows the contribution of the spots (F_s/F_{qs}) and the dashed line the contribution of the faculae (F_f/F_{qs}).

The upper right diagram of Figure 3 shows our calculations. We employed the same limb-darkening function for the undisturbed photosphere as Schatten and the same contrast functions for the active regions. We placed our bands for faculae and spots between 10° and 40° in each hemisphere. It was necessary to use very large values for the facular and spot areas to fulfil Schatten's boundary conditions of $\Delta F/F = 0.18\%$ and $F_f : F_s = 5 : 4$, namely $A_f = 34\%$ and $A_s = 2.4\%$, which is a factor of about 10 larger than observations of the active Sun imply. In agreement with Schatten we then obtain a maximal increase between $i = 90°$ and $i = 0°$ of a factor of 6, the value for the most probable inclination is a factor of about 2. The obvious qualitative difference between Schatten's result and our reproduction is probably due to the different distributions applied. Schatten has employed discrete groups of active regions whereas we have used zonal bands, that have been smeared between 10° and 40° latitude as well as over all longitudes.

As a next step we replaced the limb-darkening function of the quiet Sun and the contrasts for the spots and faculae with the calculated intensity spectra of our model and tuned the relative flux variations to fulfil Schatten's boundary conditions. The values needed were $A_f = 14\%$ and $A_s = 1.9\%$, which is still too much but remarkably less than above. The result is shown in the lower diagram of Figure 3. The variation increases now maximally by a factor of 2.7, in the most probable case, however, only by a factor of 1.3.

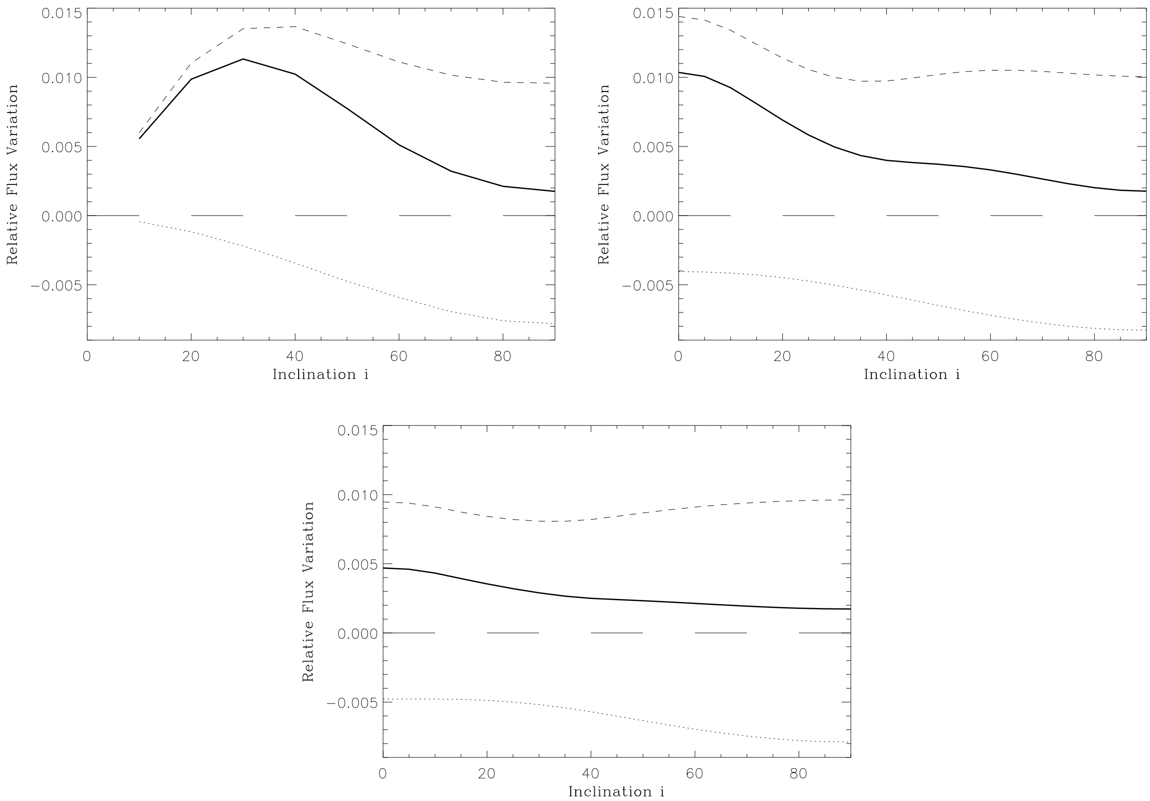

Figure 3: Relative flux variation $\Delta F/F = (F_s + F_f)/F_{qs}$ vs. inclination i (bold line) and the contribution of spots (F_s/F_{qs}; dotted) and faculae (F_f/F_{qs}; dashed). The diagram on the upper left shows Schatten's results for an initial variation of 0.18% and a flux ratio of $F_f/F_s = 5:4$ ($i = 90°$), using limb-darkening and contrast functions as described in the text. The diagram on the upper right is our reproduction under the same boundary conditions and for the same limb-darkening function and contrasts. There is a qualitative discrepancy due to different active-region distributions, but the maximum values $\Delta F/F \approx 1.1\%$ agree. The lower diagram has been calculated by replacing the limb-darkening and the contrast functions with the spectra of our model. The increase of $\Delta F/F$ is already much smaller.

Our model hence predicts a much smaller inclination effect, even if we employ Schatten's cyclic variation of 0.18% and his flux ratio of 5:4.

3.2. Radick's prediction and our results

Radick et al. [1998] applied the same limb-darkening and contrast functions as Schatten. They used an initial cyclic variation of 0.10% and a flux ratio of 2 : 1. The sunspot belts were confined to a band between 15° and 30° in each hemisphere. The facular zones ranged between 5° and 40°. These distributions were smeared completely in latitude, similar to our model. Under these conditions they found a most probable cyclic variation of 0.136% (i.e. at an inclination angle of 57°) and a maximum increase by a factor of about 2.

Again we tried to reproduce their results by employing exactly the same boundary conditions and the same limb-darkening and contrast functions. Because of the equivalent use of smeared distributions we expected better accordance this time. The left diagram of Figure 4 shows our reproduction for $A_f = 7\%$ and $A_s = 0.28\%$. We calculated a most probable variation of 0.133% and a maximum variation of 0.231%, i.e. a factor of about 2. This is in good agreement with Radick et al.

The disagreement between Schatten's prediction and the one of Radick et al. is a first clue that the inclination effect might not explain the larger variability of sun-like stars. Our calculations have introduced the spot and facular areas as a new criterion to determine the plausibility of the assumptions made by Schatten or Radick et al. Schatten's boundary conditions required an unrealistically large area for the active regions. The values assumed by Radick et al. imply a spot area of 0.28% and a ratio of $A_f/A_s = 25$. While the spot coverage of 0.28% implies a very active Sun, the facular to spot ratio is typical for a solar minimum. Measurements made during solar cycle 22 by Chapman et al. [1997] suggest a ratio of $A_f/A_s \approx 14$ and a spot area of $A_s \approx 0.2\%$ during maximum activity.

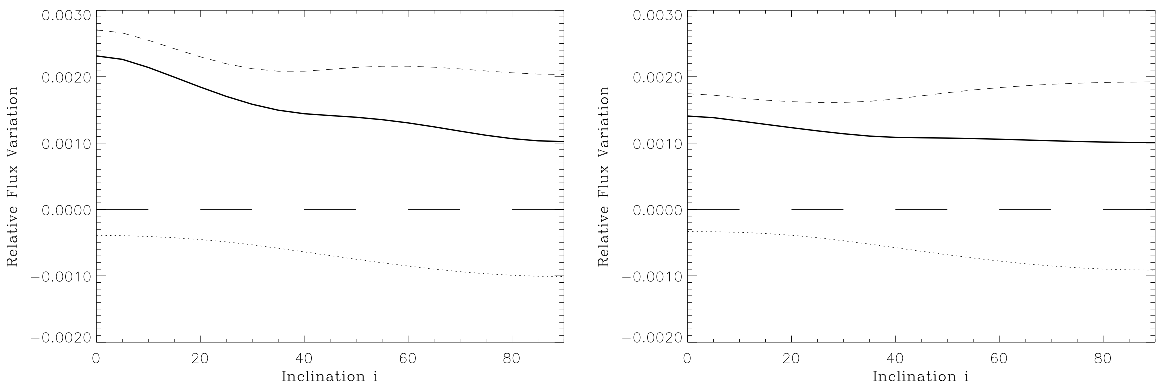

Figure 4: The left plot shows our reproduction of the inclination effect on the relative flux variations $\Delta F/F = (F_s + F_f)/F_{qs}$ (bold), F_s/F_{qs} (dotted) and F_f/F_{qs} (dashed) according to Radick et al. The right plot shows our prediction of the inclination effect, which has been calculated with the intensity spectra of our model (see text for details).

In addition, butterfly diagrams show that during activity maximum, sunspots are mainly confined to a band between 5° and 30° in each hemisphere. We hence fixed our sunspot belts in accordance with these observations and allowed the associated faculae to range between 5° and 40°. According to the observations, the spot area was fixed to $A_s = 0.20\%$ and the cyclic variation at $i = 90°$ was set to 0.10%. This yields a facular area of $A_f = 2.80\%$ and a facular to spot ratio of 14, which agrees well with what is observed for the Sun. The diagram on the right of Figure 4 shows the inclination effect calculated with our model.

We obtain a most probable amplitude for the cyclic variation of 0.106% and a maximum amplitude of 0.141%. These variations are much smaller than the values of Radick et al. This is mainly due to our different centre-to-limb variations of the facular contrasts. Radick et al. tried a second facular contrast function and found a most probable variation of 0.117% which is closer to our result. Further investigations with our model showed that changes in the spot contrast function hardly affect the gradient of $\Delta F/F$ relative to the inclination angle i, whereas changes in the facular contrast do have a great influence.

4. Conclusion

We have found that the inclination effect for the total irradiance variations of the Sun has been overestimated. Figure 5 shows our prediction in comparison with the calculations considering the model and boundary conditions used by Radick et al. [1998] and Schatten [1993]. It is very unlikely that the Sun's offset in terms of its irradiance variations (see Fig. 1b) is due to an inclination effect. We find that for a star with a similar active-region distribution as the Sun, the increase in its irradiance level does not exceed a factor of 1.5. We also find that the amount of the flux increase depends sensitively on the facular contrasts. For our input parameters, variations of the order of 10% for both the spot filling factor and the total irradiance variations resulted in a range of 1.3 to 1.5 for the maximum flux change with inclination.

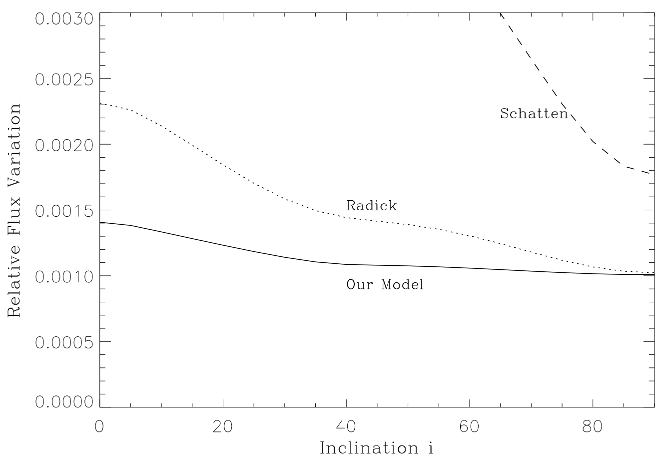

Figure 5: The inclination effect calculated with our model, respectively with the model used by Schatten and Radick.

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