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Stellar Irradiance Variations Caused by Magnetic Activity: The Influence of an Inclined Rotation Axis

R. Knaack, M. Fligge

Institute of Astronomy, ETH-Zentrum, CH-8092 Zurich, Switzerland

S.K. Solanki

Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany

Y.C. Unruh

Institute of Astronomy, University of Vienna, Türkenschanzstr. 17, A-1180 Vienna, Austria

Abstract. We examine the influence on irradiance variations and Ca II H&K flux due to the inclination of the rotation axis of a Sun-like star relative to the observer. Wavelength-dependent intensity spectra are used to determine the contributions from the undisturbed photosphere, sunspots and faculae. We find that an inclined rotation axis increases the total solar (stellar) irradiance variations maximally by 40%. This is much less than former studies (Schatten 1993, Radick et al. 1998), which used simple contrast functions, suggested. The most probable value is approximately 6%. In the averaged Strömgren filters (b+y)/2, we estimate a most probable increase of the solar variability of 30% due to the inclination effect. In addition, we find that the observed Ca II H&K flux depends only marginally on the inclination angle. However, this angle does affect the chromospheric variability of Sun-like stars. Nonetheless, our results indicate that the inclination effect cannot explain the discrepancy between the brightness variations of the Sun and Sun-like stars.

1. Introduction

Measurements of stellar Ca II H&K fluxes (used as a proxy of chromospheric magnetic activity) and contemporaneous Strömgren b&y photometry (at 472 nm and 551 nm, respectively) have revealed that the photometric variability of the Sun, which has an amplitude of 0.1% (Fröhlich 2000), is a factor of about 2-3 smaller compared to Sun-like stars of similar magnetic activity (Lockwood et al. 1992, Radick et al. 1998).

The special position of a terrestrial observer, who sees the Sun almost equator-on, combined with the fact that solar active regions are confined to low latitudes has been proposed as a possible explanation for the subdued variability of the Sun (Schatten 1993). An observer high above the ecliptic plane, however, would see sunspots and faculae apparently closer to the solar limb.

This affects the observed solar irradiance variations because white-light faculae have a higher contrast near the limb than at disc center while the contrast of sunspots changes only slightly with limb distance. Altogether, a net increase of total irradiance variations is expected when viewing the Sun out of the equatorial plane. Therefore, assuming a random distribution of stellar rotation axes with a most probable inclination of 57°, this effect tends to enhance the photometric variability of Sun-like stars.

At the same time we expect the apparent activity level, as judged by the star's Ca II H&K flux, to decrease with decreasing inclination since the Ca II H&K intensity contrast is roughly independent of limb-distance and the projected area of the active latitude bands decreases with inclination.

2. Method

We calculated the relative flux variations ΔF produced by a given distribution of faculae and spots on the surface of the Sun as a function of inclination i (defined as the angle between the solar rotation axis and the line-of-sight) and wavelength λ, yielding $\Delta F_\lambda(i)$. The intensity spectra of the employed three components (faculae, sunspots and undisturbed photosphere) were calculated using Kurucz' spectral synthesis code ATLAS9 (Kurucz 1992) and opacity functions from plane-parallel model atmospheres for each component. A detailed description of the spectra is given by Unruh et al. (1999).

3. Results

We restricted our input parameters to the following *observed* values: (i) a total spot coverage of $A_s = 0.20\%$, (ii) a total irradiance variability of $\Delta F(90°) = 0.10\%$ and (iii) activity belts ranging from 5° to 30° for spots and from 5° to 40° for faculae. This yielded a total facular area of $A_f = 2.8\%$, which is in good agreement with observations during solar activity maximum (Chapman et al. 1997).

3.1. Relative flux variations

For the total wavelength range we have obtained a most probable amplitude of $\Delta F(57°) = 0.106\%$ and a maximum amplitude of $\Delta F(0°) = 0.141\%$. These variations are significantly smaller than the values found by Schatten (1993) or Radick et al. (1998), which is summarized in Fig. 1a. Both used the empirical model of Sofia et al. (1982), where the limb-darkening of the undisturbed photosphere and the contrasts of spots and faculae are described by second degree polynomials. Note that the spectra we used satisfy a number of observational constraints (Unruh et al. 1999; Fligge et al. 2000).

The relative flux variation ΔF as a function of wavelength λ is shown in Fig. 1b for the inclinations $i_1 = 90°$, $i_2 = 57°$ and $i_3 = 0°$. The sharp rise for $\lambda < 450\,\mathrm{nm}$ is due to the increasing facular contribution in the ultraviolet. Note that the solar variability decreases with decreasing inclination for $\lambda \lesssim 400\,\mathrm{nm}$, thus $\Delta F(i = 90°) > \Delta F(i < 90°)$, which is the opposite behavior compared to wavelengths longer than 400 nm. This is seen more clearly in Fig. 1c where the relative change of ΔF, thus $[\Delta F(i_{2,3}) - \Delta F(i_1)]/\Delta F(i_1)$, is plotted. The reason lies in the center-to-limb variation of the facular contrast. For $\lambda < 400\,\mathrm{nm}$, the increase of the contrast from disc center to the limb is too small to compensate for the reduction in projected facular area.

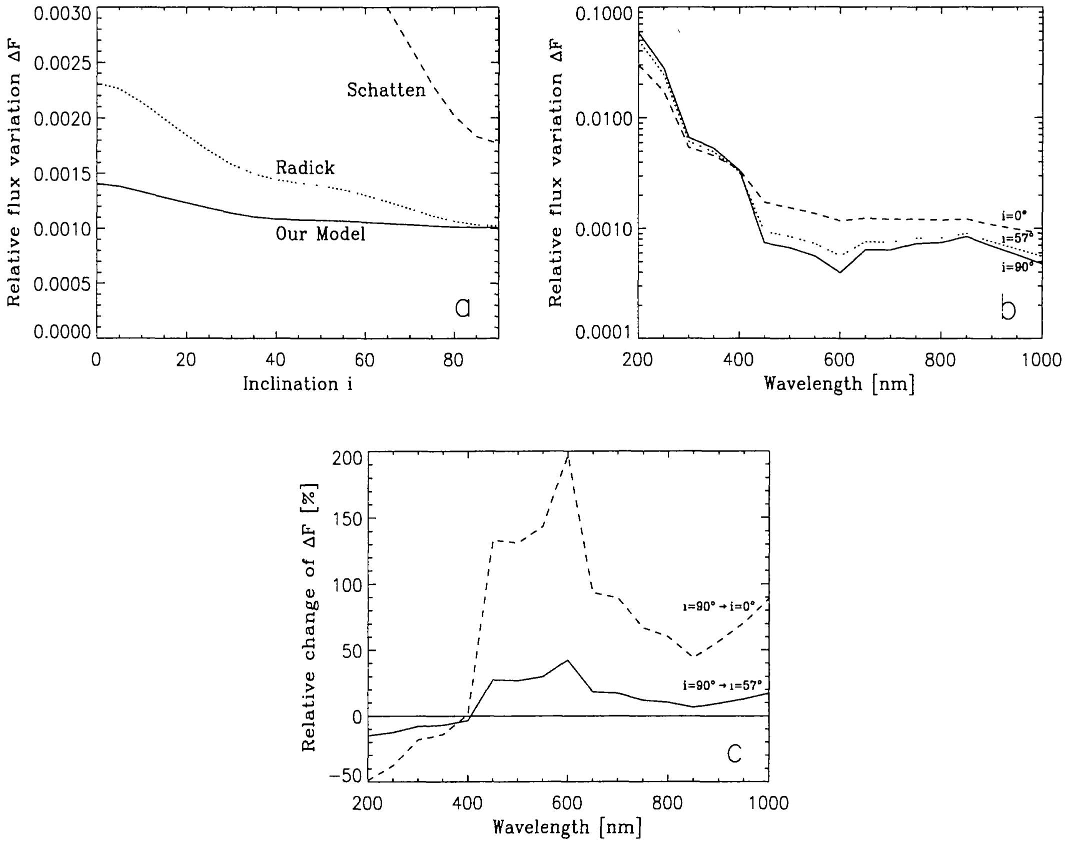

Figure 1. *Panel a:* Relative flux variation ΔF vs. inclination i for the total wavelength range. The result of our model (solid line) is compared to the reproduction of the results of Radick et al. (1998) (dotted) and Schatten (1993) (dashed), respectively. *Panel b:* ΔF vs. wavelength λ for the inclinations $i = 90°$ (solid), $i = 57°$ (dotted) and $i = 0°$ (dashed). *Panel c:* Relative Change of ΔF.

3.2. Ca II flux

An instrumental index of the Ca II H&K flux is the S-index. We investigated the S-index of the Sun at activity maximum as a function of i, which is shown in Fig. 2. As i changes from 90°to 0°, S drops from 0.193 to 0.182, i.e. by only 6%. However, the inclination effect is much larger for $\Delta S = S - S_{qs}$, where $S_{qs} = 0.169$ is the S-index of the Sun at activity minimum and hence independent of i. From 90°to 57°, ΔS decreases by 15% and from 90°to 0°even by 46% (i.e. nearly by a factor of 2).

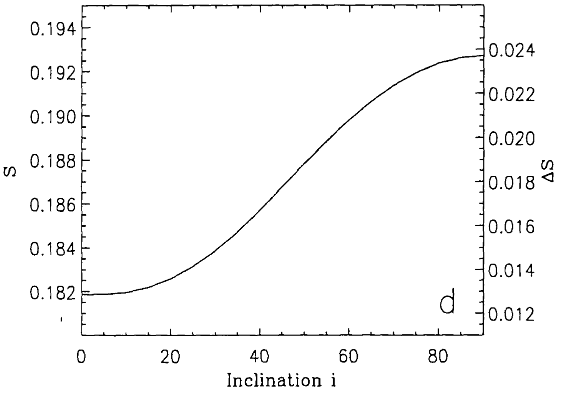

Figure 2. S-index vs. i for the active Sun (left axis) and $\Delta S = S - S_{qs}$ vs. i (right axis).

4. Conclusions

The influence of an inclined rotation axis on the total irradiance variations of the Sun has been overestimated. Using intensity spectra and relative parameters, we predict an increase of the variability of 6% when decreasing i from 90°to 57°, and a maximum increase of 40% when decreasing i from 90°to 0°.

For the spectral irradiance variations in the Strömgren b&y filters (applied in stellar photometry), we estimate a most probable increase of roughly 30% for the averaged (b+y)/2 filter when decreasing i from 90°to 57°.

The cyclic Ca II flux variation of the Sun between activity minimum and maximum strongly depends on the inclination of the rotation axis relative to the observer. This result indicates that the temporal chromospheric variability of Sun-like stars is systematically underestimated. However, the averaged Ca II flux depends only marginally on the inclination.

Therefore, it appears unlikely that the moderate irradiance variations of the Sun can be explained by an inclination effect.

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