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Variations of the Solar Spectral Irradiance

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Abstract. The relative variation of the solar irradiance depends strongly on the wavelength band, with the shortest wavelengths exhibiting the largest variations over the solar cycle. This means that not only the total irradiance varies with solar activity but also the shape of the solar spectrum. These measured effects have been successfully modelled. The models indicate that more than 90% of the total and spectral irradiance variations over the solar cycle are due to the magnetic field at the solar surface. The solar spectral irradiance variations play an important part in constraining the models, since they can directly distinguish between changes in the solar effective temperature and changes produced by variations of solar surface magnetic flux. They also help to determine what fraction of the total solar radiative input to Earth is absorbed by the Earth's atmosphere.

1. Introduction

The total irradiance of the Sun varies as active regions and sunspots pass over the solar surface in phase with its rotation and along with the rise and fall of solar magnetic activity over the solar cycle (Fröhlich 2000; Lean 2001). Allied to these changes in brightness of the solar disc are variations of its spectrum. Hence, as the total solar irradiance varies, the irradiance or flux at some wavelengths changes more strongly than at others.

Since the total solar irradiance is simply the integral over wavelength of the spectral irradiance, the latter obviously contains considerably more information than the former. Consequently, studying spectral irradiance variations provides additional important constraints on the physical origin of irradiance variations. The following sources of solar irradiance variations have, among others, been proposed in the literature:

- the magnetic field at the solar surface (Foukal & Lean 1986; Solanki & Fligge 2001);

- changes in the convection caused by the magnetic field in the Sun's interior or by other mechanisms (Parker 1987; Kuhn 1996);
- r-modes (slow oscillations driven by solar rotation, Wolff & Hickey 1987a, b).

The spectral irradiance also holds the key to determining which layers of the solar atmosphere provide the largest contribution to the total irradiance variations, or whether it is spectral lines or the continuum whose influence dominates.

A detailed knowledge about the spectral composition of solar irradiance and it variations is also crucial regarding the solar-terrestrial relationship. In particular, the influence of solar radiation on stratospheric chemistry is strongly wavelength dependent. For example, solar UV radiation longward of approximately 200 nm is absorbed by the Hartley band of O_3 and leads to the destruction of stratospheric ozone. Shortward of this wavelength the radiation is absorbed by O_2 and hence contributes to ozone production. Thus Larkin, Haigh & Djavidnia (2000) have shown that the change in atmospheric absorption of solar radiation between activity minimum and maximum depends strongly on the wavelength dependence of the solar irradiance variations, being larger if the detailed spectral variations as computed by Solanki & Unruh (1998) are employed, than if the solar irradiance is assumed to vary in a wavelength-independent way. This illustrates the importance of knowing the relative strength of the irradiance variations at different UV wavelengths over the solar cycle.

Finally, a knowledge of the solar spectral variability is useful when comparing solar irradiance variations with those of other cool stars (Radick 2001), because stellar fluxes are generally measured in given wavelength bands. The variability of the radiation in these bands may differ significantly from that of the spectrally integrated irradiance (measured for the Sun).

2. Measurements of Spectral Irradiance Changes

Prior to SOHO spectral irradiance measurements were restricted to the UV spectral range. Most early long-term UV irradiance variability measurements for the Sun were obtained using the Mg II index (Heath & Schlesinger 1986) that measures the Mg II h & k core-to-wing ratio. The cores of the Mg II h & k lines sample relatively high layers of the solar atmosphere and are strongly influenced by changes in solar activity while the wings are almost unaffected by such changes. The core-to-wing ratio is hence a very sensitive measure of solar activity. As it is the ratio that is measured rather than absolute flux, the Mg II index also largely avoids problems due to instrument degradation. Furthermore, the wing measurements are selected to be roughly equidistant from the line core so that linear wavelength-dependent effects cancel out.

There is now a long time series of the Mg II index available that goes back to 1978 and was taken mainly with the SBUV (Solar Backscatter Ultra Violet) instruments onboard Nimbus 7 and various NOAA satellites. The solar-cycle amplitude of the Mg II index between cycle 21 – 22 minimum and cycle 22 maximum is about 8%. While rotational modulation can reach 7% during active periods, it tends to be below 2% during cycle minima (DeLand & Cebula 1998).

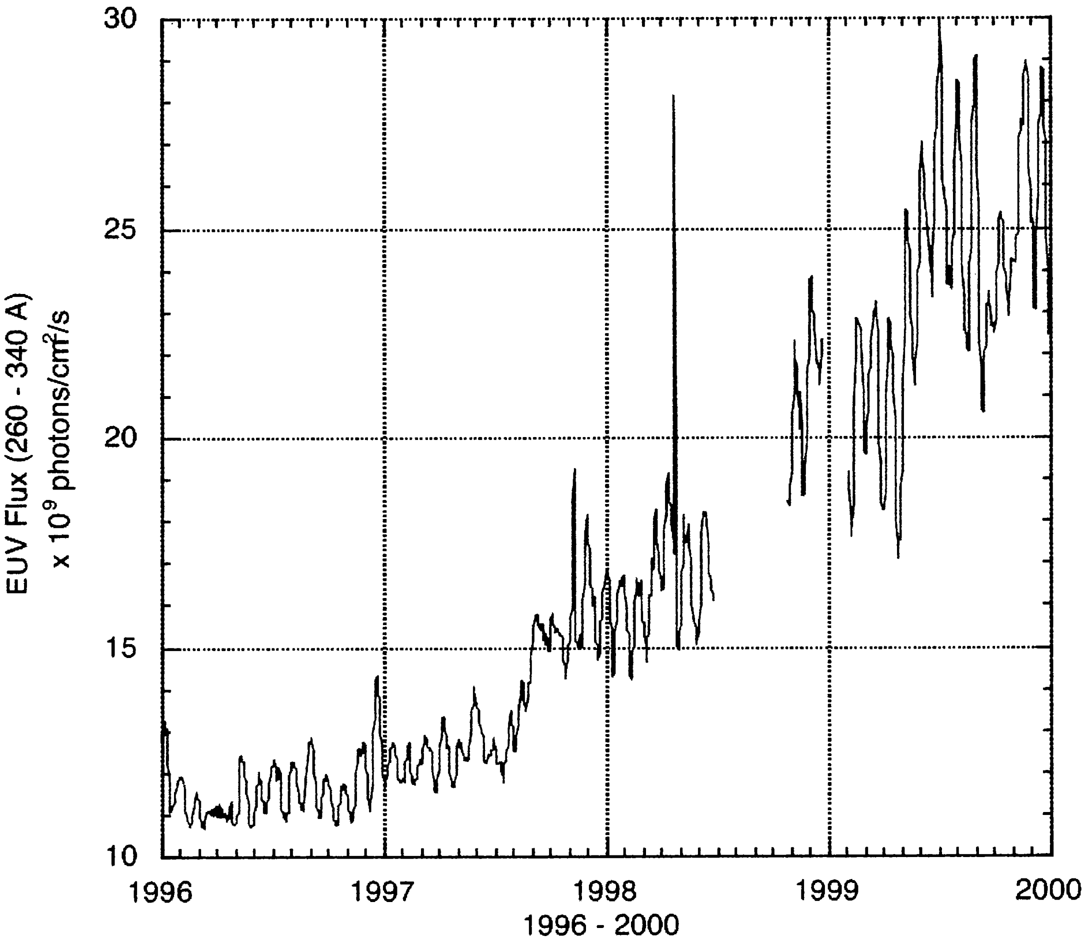

Figure 1. Solar irradiance in the wavelength range 24–36 nm since 1996 recorded by the SEM instrument on board SOHO. The gaps in the time series are due to the loss of contact with SOHO and for related reasons. (Courtesy of SOHO/SEM consortium)

The variability of the Mg II index can be used as a proxy to estimate the spectral irradiance variability between 165 and 400 nm through scale factors (Heath & Schlesinger 1986; Cebula, DeLand & Schlesinger 1992). The scale factors are derived by linear regression of the Mg II index and measurements in individual wavelength bins. It turns out that the Mg II index represents the irradiance variation around 200 nm very well. From about 210 to 250 nm (the Al I to Mg I edge) the variability then drops to roughly half of the Mg II index variability. For wavelength bins redward of 300 nm, however, the scaling errors are of the order of the scale factors themselves or even larger.

In September 1991, close to solar maximum, NASA's Upper Atmosphere Research Satellite (UARS) was launched. On board were two instruments to measure the full-disk spectral irradiance variations in the UV, namely SUSIM (Solar UV Spectral Irradiance Monitor; Brueckner et al. 1993) and SOLSTICE (SOLar STellar Irradiance Comparison Experiment; Rottman, Woods & Sparn 1993). As opposed to earlier instruments, SUSIM and SOLSTICE have onboard calibration facilities. This allows measurements of the solar spectral irradiance variability without the intermediary of an index such as the Mg II core-to-wing ratio. Both instruments operate in the wavelength range from approximately 120 nm to 410 nm and their accuracies greatly improve on earlier instruments. Floyd et al. (1998) display the spectral irradiance variations between solar minimum and maximum in the range from 120 to 400 nm derived from SUSIM measurements. They find very strong variability at the lowest wavelengths, e.g. at Lyman α, where it exceeds 100%. Above 170 nm the variability drops below 20% and then to about 4 to 5% longward of the Al I edge at 208 nm. Above 300 nm the variability is of the order of 1% or lower.

White et al. (1998) and Cebula & DeLand (1998) have compared the Mg-index variability as measured by the SBUV, SUSIM and SOLSTICE instruments. The agreement between SBUV and SUSIM is of the order of 1%. The agreement with the SOLSTICE index is harder to judge as the resolution of SOLSTICE (≈ 0.2 nm) is about a factor of 5 higher than that of SUSIM and SBUV. The SOLSTICE index is, as a consequence, roughly twice as sensitive to changes in solar activity. Woods et al. (1996) have compared nearly simultaneous flux measurements by SUSIM (UARS), SOLSTICE and instruments flown during the first two Atlas missions. While the agreement between all 4 instruments (at the 2σ level) is between 5 to 10% at all wavelengths, the agreements between the two UARS instruments is better than 2% for wavelengths greater than 160 nm, which is unfortunately still not good enough to track the solar-cycle variations in the 300 to 400 nm range.

To obtain the spectral behaviour of the irradiance changes between solar maximum and minimum over a wide wavelength range, Lean et al. (1997) collated data from several missions and estimated the changes in the near UV with UV-sunspot darkening and facular indices.

There are two instruments on SOHO, which have contributed significantly to our knowledge of solar spectral irradiance variations. One is the SEM (Solar EUV flux Monitor; Ogawa et al. 1998), which is a part of the CELIAS (Hovestadt et al. 1995) package. SEM measures solar EUV irradiance in three channels between 17 nm and 70 nm. The results for the 26-34 nm channel are plotted in Fig. 1. The large (more than 100%) and rapid increase of the irradiance at these short wavelengths from solar activity minimum towards maximum is striking.

VIRGO (Variability of Irradiance and Gravity Oscillations) has undertaken the difficult task of obtaining an estimate of the very much smaller changes of the irradiance in the visible spectral range with the help of three photometers sampling the solar spectrum in the blue (402 nm), green (500 nm) and near IR (862 nm). As in the UV the roughly 27 day modulation of the signal by solar rotation is very prominent. Unlike the UV, however, not only the brightening due to faculae but also the darkening due to sunspots (prominent at around day 330 or 610) contributes to the variability. The trend gleaned from the UV data that the shorter the wavelength the larger the variability also appears to be roughly satisfied by the VIRGO data, with the blue channel showing the largest variability and the IR channel the smallest.

Due to the lower stability of the photometers relative to the VIRGO radiometer, which measures the total irradiance, the long-term trends in irradiance exhibited by the three filters are not very reliable. This is one of the missing

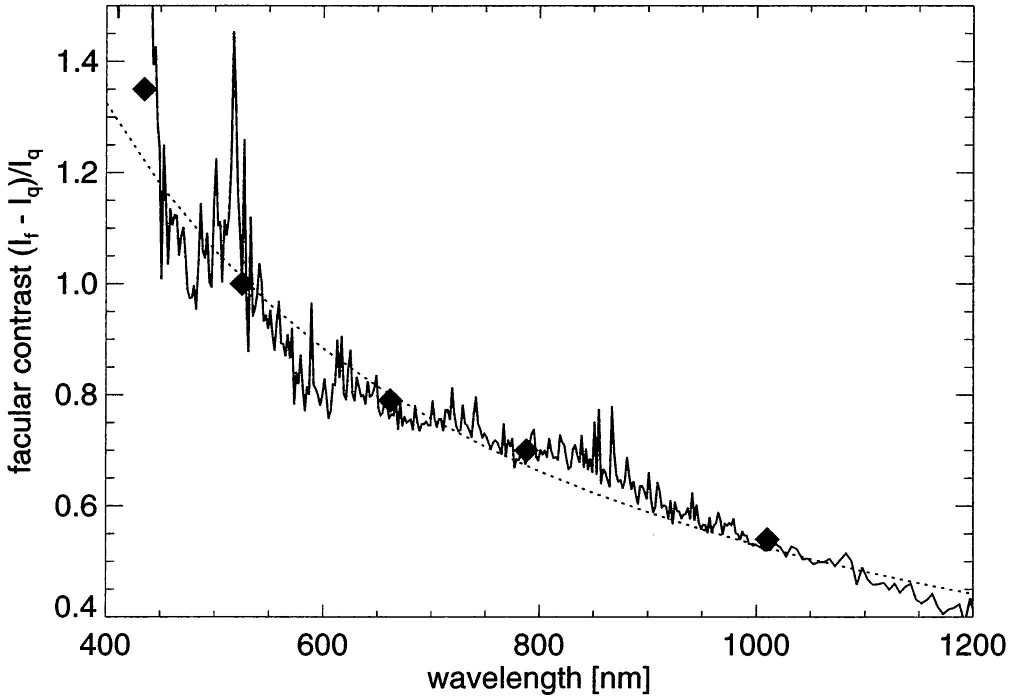

Figure 2. Intensity contrast of faculae vs. wavelength. Observational results are indicated by the filled diamonds, the model predictions by the solid curve. The plotted values correspond to $\mu = 0.25$, where μ is the heliocentric angle (from Unruh et al. 1999).

pieces of data which a future spectral irradiance instrument will need to provide. Also missing is any knowledge of the irradiance at still longer wavelengths. Many of these points will be addressed by the upcoming SORCE (SOlar Radiation and Climate Experiment) mission of NASA (Rottmann, Woods & Sparn 2001), which is also expected to provide more accurate UV irradiance measurements.

3. Modelling Spectral Irradiance Variations

All successful models presume that the underlying agent of solar irradiance variations, be they total or spectral, is the magnetic field at the solar surface, i.e. in the photosphere. In that layer the magnetic field is concentrated into flux tubes, visible in cross-section at the solar surface. They range from the small and bright magnetic elements to the larger and dark sunspots. The former cluster together to form the magnetic network (in the quiet Sun) and faculae (in active regions). To make a quantitative estimate of the contribution of these features to the irradiance time series we need to know the spectrum of each of these types of features for different positions on the solar disc, as well as the

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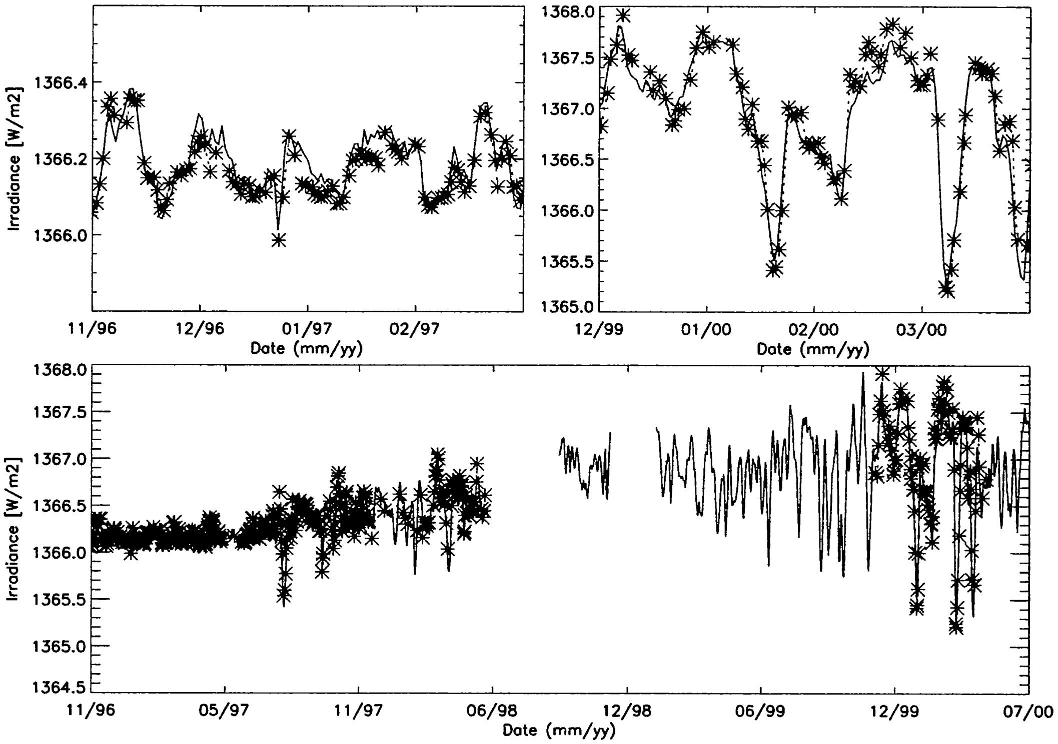

Figure 3. Measured (solid curve) and modelled (stars and dashed curve) total solar irradiance records for the period of time covered by VIRGO. The two upper frames show enlarged sections of the whole time series (lower frame). Note the good agreement. VIRGO level 3.1 data have been employed, which include the corrections proposed by Fröhlich & Finsterle (2001).

fraction of the solar disc such features cover and where they are located at any given time.

To keep the model simple we describe the atmosphere within sunspots, faculae, the network and the quiet Sun by plane-parallel models, thus neglecting the fine scale structure, e.g. due to the flux tubes in the faculae. We further assume that four model atmospheres are sufficient for our purposes (one each describing sunspot umbrae, penumbrae, quiet Sun and faculae). The adopted models for each of these features satisfy a number of observational constraints. As an example we show in Fig. 2 the spectral contrast between faculae and quiet Sun at $\mu = 0.25$ as predicted by the adopted model (solid line) and as measured by Chapman & McGuire (1977; filled diamonds). More details are given by Unruh, Solanki & Fligge (1999).

Next we use daily MDI magnetograms and white-light images to identify network, faculae and sunspots on the solar disc. The two ingredients, used to derive time series of maps of the distribution of the facular and sunspot components, and a grid of spectra for various limb distances calculated using the atmospheric models, together make it possible to reconstruct both total and spectral irradiance. Further details are given by Fligge, Solanki & Unruh (2000), Fligge et al. (2001) and Solanki & Fligge (2001).

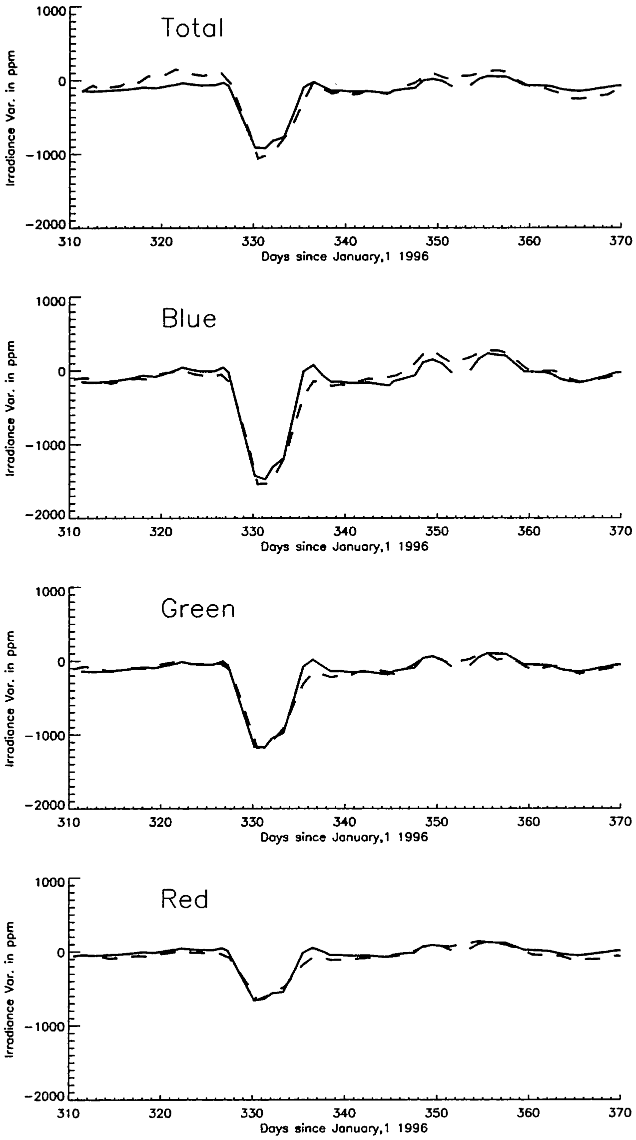

Figure 4. Comparison between total and spectral irradiance measured by VIRGO and reconstructed by the model of Fligge et al. (2000) for a period of two months during which a spot-dominated active region crossed the solar disc.

Consider now the results of this approach; the results of simpler models have been reviewed by Lean (2001). A detailed reconstruction of the total irradiance has so far been carried out for the period from the launch of SOHO to its temporary loss, as well as around the maximum of cycle 23. Measured (solid) and reconstructed (stars) total solar irradiance is plotted in Fig. 3. The good correspondence between the two quantities over the whole period of the reconstruction is gratifying. Note that a discrepancy between VIRGO observations and models that was present in the second half of 1996 in earlier versions of the modelling may be due to calibration problems in VIRGO and practically vanishes when a correction to the VIRGO data is introduced (Fröhlich & Finsterle 2001).

Fig. 4 shows that the same model also reproduces the records obtained from the three VIRGO photometers, at least on a short time scale. Recall that these photometers do not posses the necessary long-term stability to allow a comparison between observed and reconstructed time series on such long time scales.

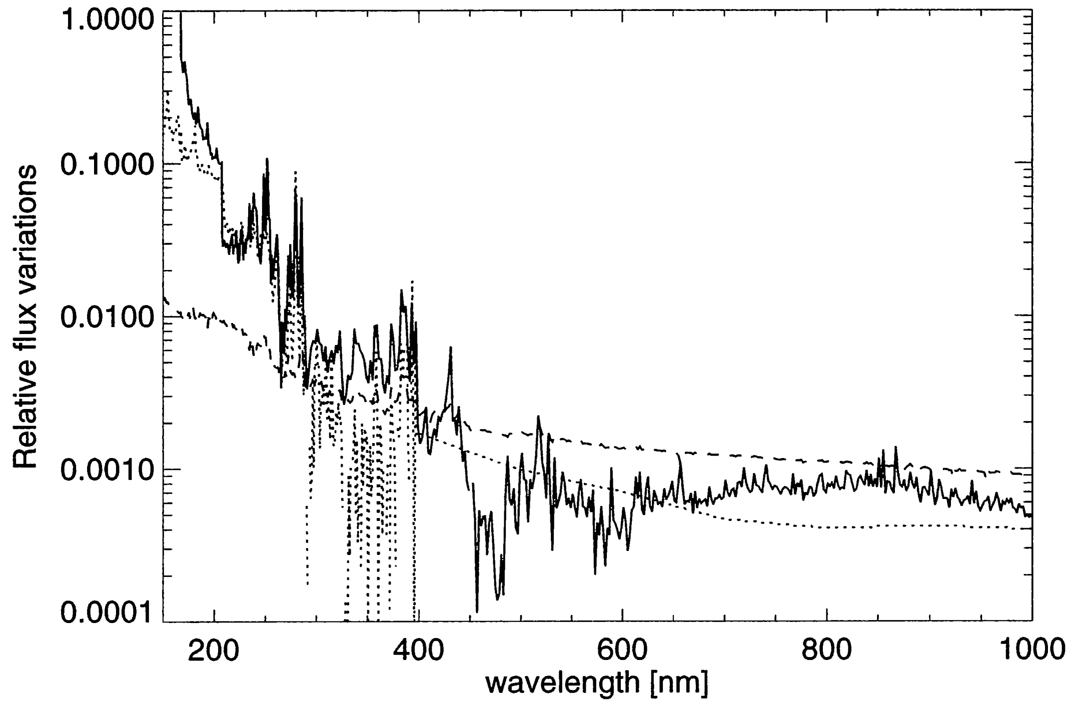

Figure 5. Relative change in the solar spectral irradiance between solar activity maximum and minimum plotted vs. wavelength. The dotted curve represents the measurements (Lean et al. 1997), the solid curve our model and the dashed curve the expected result for a global change in effective temperature by 1° of the Sun. The facular and spot filling factors used to calculate the model change are 3.2% and 0.3% respectively.

Next, in Fig. 5, we compare the relative change of the spectral irradiance over the solar cycle. Plotted vs. wavelength is the irradiance at solar maximum minus irradiance at minimum normalized to the irradiance at minimum. Note the logarithmic scale for the flux variations. The observations, represented by the dotted line, are restricted to wavelengths smaller than 400 nm (and are reliable only below 300 nm). The reconstructed irradiance variations, indicated by the solid line, are only reliable for wavelengths above 180 nm (cf. Solanki & Unruh 1998). At shorter wavelengths NLTE effects, which are not included in the models described here (but see Fontenla et al. 1999), become too important to be neglected. To highlight the great sensitivity of the spectral variability to the exact change in the atmospheric structure with solar activity we have also plotted (dashed curve) the result expected if only the effective temperature

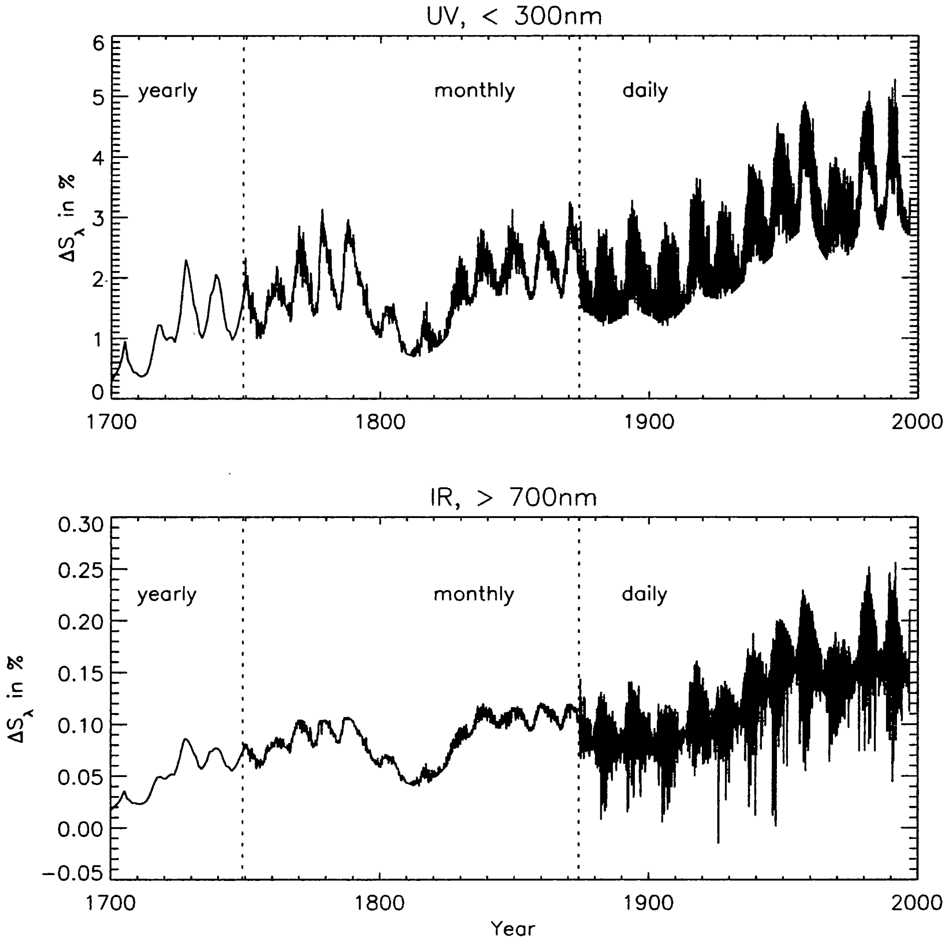

Figure 6. Reconstructed spectral irradiance in two spectral bands, namely for wavelengths below 300 nm (top) and above 700 nm (bottom). (Adapted from Fligge & Solanki 2000.)

of the Sun were raised by 1°. This temperature enhancement corresponds to an increase of 0.1% in the total irradiance. Obviously the latter proposal is inconsistent with these data.

In addition to the successes of the model outlined above, it also gives the correct faculae-to-sunspot area ratio at the different phases of the solar cycle (Chapman, Cookson & Dobias 1997; Fligge et al. 1998), as well as the relative variation of the line blanketing over the solar cycle (Mitchell & Livingston 1991; Unruh et al. 1999).

In summary, there is now strong evidence that over 90% of the measured variations of the solar total and spectral irradiance are due to the magnetic field at the solar surface.

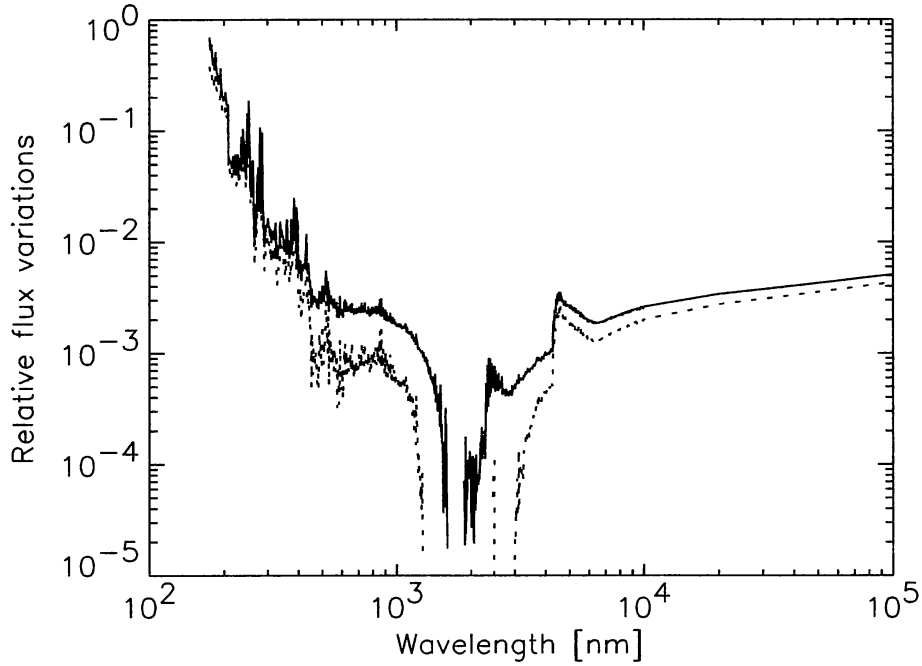

Figure 7. Relative solar irradiance changes between (present-day) activity maximum and minimum (dotted line) as well as between (present-day) activity minimum and the Sun in a Maunder minimum state (solid line).

4. Reconstructing Past Spectral Irradiance

Once the spectrum of magnetic features has been determined (see Unruh et al. 1999) and our understanding of how spectral irradiance variations are caused has been tested (see Sect. 3) it is possible to reconstruct the spectral irradiance back to the Maunder minimum under certain conditions and assumptions (see Fligge & Solanki 2000; Lean 2001). The reconstruction on such time scales has in the past been practised mainly for the total solar irradiance (e.g. Hoyt & Schatten 1993; Lean, Beer & Bradley 1995; Solanki & Fligge 1998, 1999; Lockwood & Stamper 1999). Recently Fligge & Solanki (2000) and Lean (2001) have extended such reconstructions to include the change in the spectrum since the Maunder minimum. This approach assumes that all variations in irradiance are due to surface magnetism or have a similar spectral dependence. The exact influence on the spectrum of convection changes or of other mechanisms is unknown. However, it is expected to be different from the influence of sunspots and faculae.

One reconstruction of the irradiance since 1700 is plotted in Fig. 6 (Fligge & Solanki 2000). Displayed are the results for two wavelength bands, one in the UV (averaged over $\lambda < 300$ nm) and one in the IR ($\lambda > 700$ nm). As expected, the increase in irradiance since the Maunder minimum is 20 times larger in the UV than in the IR. The reconstruction is more reliable since 1874 when it becomes possible to distinguish between the influence of sunspots and active region faculae in a more straightforward way. The reconstruction for this period shows that sunspots produce a larger *relative* influence in the IR than in the UV (although the *absolute* value of the dips in the UV due to sunspots is larger than in the IR). This is due to the fact that the intensity contrast of faculae decreases more rapidly with increasing wavelength than the contrast of sunspots. Fligge & Solanki (2000) have also calculated the relative change in the solar spectrum between the Maunder minimum and the minimum between cycles 22 and 23. They have compared this with the relative change between minimum and maximum solar activity of cycle 22. These results are plotted in Fig. 7. Note that the spectral change between the Maunder and present-day activity minima is much stronger at visible and IR wavelengths than the variations between present-day activity minima and maxima. The seemingly large dip in contrast around 1.6 μm appears greatly enhanced due to the logarithmic scale. Since the contrast there is very small even minor errors in the employed temperature stratifications have a large influence on the figure.

Partly due to the paucity of historical records the reliability of the results presented in this section is far lower than of the work reviewed in other sections. It is therefore likely that reconstructions made in the future will differ quantitatively, although probably not qualitatively, from those presented here.

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