PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 63 (2001) 1479–1487

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Variations of solar spectral irradiance from near UV to the infrared—measurements and results

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Received 5 January 2000; received in revised form 6 December 2000; accepted 15 March 2001

Abstract

Solar spectral irradiance variations are known to exhibit a strong wavelength dependence with the amount of variability increasing towards shorter wavelengths. The bulk of solar radiation is emitted at visible and infrared wavelengths. Thus, the spectral radiation length of 300 nm accounts for 99% of the total solar radiative output. Deposited in the Earth's troposphere and biosphere, this part of the solar irradiance spectrum determines direct solar radiative forcing and is therefore of particular interest for climate studies. First, measurements of solar irradiance and irradiance variability from near UV to the IR are reviewed with particular emphasis on the results obtained from the Variability of Irradiance and Gravity Oscillations (VIRGO) on SOHO and Solar Spectrum Measurement (SOLSPEC) instruments. In the second part a model is presented which describes solar spectral irradiance variations in terms of the changing distribution of solar surface magnetic features.

Keywords: Solar spectral irradiance; Irradiance variability; Solar surface magnetic features

1. Introduction

The history of solar irradiance measurements has its beginnings around the middle of the last century when people like Pouillet and Herschel started to use for the first time pyrheliometry to estimate the total solar radiative output. In succeeding years, observers like Langley (1876, 1884) or Abbot (Abbot and Fowle, 1911; Abbot, 1934) derived values for the total solar irradiance which were remarkably close to the modern value of about 1368 W/m^2. Obviously, these early observations were Earth-bound which rendered it difficult to achieve a precision high enough to detect irradiance *variations* due to our lack of knowledge about the transmissivity variations of the Earth's atmosphere.

Space-borne measurements of solar irradiance are now available for more than 20 years. They changed our picture of the Sun's radiative output completely. What once was called the "solar constant" turned out to be surprisingly variable on very different time-scales ranging from minutes up to decades and probably even longer. Most prominent is a 0.1% increase of total solar irradiance in phase with the solar magnetic activity cycle.

Solar irradiance variations also show a strong wavelength dependence with a dramatic increase towards shorter wavelengths. Variations at UV and shorter wavelengths exceed those in the visible by orders of magnitude. Although the contribution of UV radiation to total solar irradiance is rather small, it contributes substantially to the total irradiance variations.

In this review, we focus on the solar spectrum in the near UV, visible and infrared, i.e. at wavelengths between 300

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1364-6826/01/$ - see front matter
PII: S1364-6826(01)00020-7

and 10,000 nm. The solar radiation at these wavelengths is of special interest for both solar physics and climatology for the following reasons: Firstly, most of the solar radiative output (99%) occurs at these wavelengths. Hitting the Earth, radiation from this part of the spectrum that is not scattered back into space by the Earth's atmosphere, clouds and the surface is absorbed in the biosphere, the surface and the oceans where it, hence, directly determines the thermal energy balance of the Earth's atmosphere. Secondly, this part of the spectrum, formed mostly deep down in the solar photosphere, holds the key to unraveling the relation between solar surface (magnetic) features and total or spectral solar irradiance changes.

On time-scales of the solar cycle and less, a considerable part of the irradiance variations is associated with the changing distribution of sunspots, faculae and bright network elements. While sunspots dominate short-term changes on time-scales of a few days to weeks (Willson et al., 1981; Hudson et al., 1982; Fröhlich et al., 1994), faculae and, in particular, the enhanced network are supposed to live much longer and, therefore, seem to contribute significantly to the variability of the solar cycle (Foukal and Lean, 1988; Fröhlich and Pap, 1989; Pap, 1998).

While the thermal structure of sunspots is well known (Severino et al., 1994; Ruedi et al., 1997; Del Toro Iniesta et al., 1994), the temperature stratification of the small-scale magnetic features which constitute the faculae and enhanced network is less well established. The low contrast and complex morphology of these features hinder reliable measurements; and various observations give widely different contrast values (Frazier, 1971; Auffret and Muller, 1991; Wang and Zirin, 1987; Taylor et al., 1998; Lawrence, 1988; Ahern and Chapman, 2000). This lack of knowledge renders it almost impossible to adequately model the brightening of small-scale surface magnetic features and represents one of the major source of errors of present irradiance reconstructions. The employment of new techniques, such as the inversion of polarized spectra is expected to help improve this situation (Ruiz Cobo and Del Toro Iniesta, 1992, 1994; Frutiger et al., 1999).

In the discussion to follow, we give an overview of ground-based and space-borne measurements of the solar irradiance spectrum as well as measurements of relative irradiance variations in Section 2. Spectral irradiance variations are discussed in Section 2.1, while we focus on short-term variations in Section 2.2. In Section 3, we illustrate how well even a simple model based on surface magnetic features can account for these observations.

2. Observations

Ground-based measurements of solar irradiance are limited by the absorption of large parts of the original solar spectrum by the Earth's atmosphere which blocks or at least strongly attenuates most of the solar UV and infrared radiation. Already the earliest observers, therefore, chose high mountain peaks to perform their measurements in order to minimize the influence of the Earth's atmosphere. Stratospheric absorption, however, which mainly affects the UV part of the solar spectrum, must nevertheless be accounted for. This is generally done using the Langley (Langley, 1876) method which measures the incoming solar radiation at different zenith distances of the Sun and extrapolates to zero airmass.

Measurements by, e.g. Labs and Neckel (1962), are of that kind. Using the Langley method, they obtained an absolute value for the disk center intensity, $I^c(\lambda)$, at a given wavelength λ. After detailed corrections of $I^c(\lambda)$ for the center-to-limb variation (CLV; Neckel and Labs, 1984) they obtained a value for the solar irradiance by integrating over the full solar disk. Fig. 1 shows the result of these measurements (thin solid line). The spectral resolution is between 1 and 5 nm depending on the wavelength range and the absolute accuracy of the irradiance values is of the order of 1–2%. As can be seen, the solar spectrum follows a black body radiation curve of about 5770 K (thick curve), particularly at longer wavelengths. In the UV and in much of the visible, the solar spectrum is heavily blended by strong spectral lines due to the increased opacity of the solar atmosphere at these wavelengths which is responsible for the substantial deviations from the black body curve.

Although, performed more than 30 years ago, the measurements of Neckel and Labs are still widely used and serve as a (low resolution) reference spectrum. Recent measurements by Burlov-Vasiljev et al. (1998b, a) achieve similar results and comparable precision.

Relative irradiance variations near UV, visible and infrared wavelengths are on the order of 0.1% and less. Therefore, the detection of irradiance variations in this part of the solar spectrum is difficult from the ground although the sign and magnitude of the short-term variations seen in the pyrheliometry agrees well with the Abbot (1942) data (Foukal and Vernazza, 1979).

Different steps to overcome the problems caused by the Earth's atmosphere and to access the full solar spectrum have been undertaken. For example, Arvesen et al. (1969) and Thekaekara (1976) used an airplane as their platform to perform the measurements, while Wehrli (1992) used balloon flights. It was the possibility of space-flights which finally enabled an unaltered view of the complete solar spectrum and provided the basis for several long-term solar monitoring programs (Hickey et al., 1988; Hoyt and Kyle, 1990; Willson and Hudson, 1988, 1991; Fröhlich et al., 1997).

Most of the space-borne instruments were designed to measure solar UV radiation below 300 nm, making use of larger variations of the solar irradiance at shorter wavelengths (see, e.g., Lean, 1991 for an overview). Some, however, also included the near UV range between 300 and 400 nm. Of these, several NOAA satellites (Heath and Schlesinger, 1986; Schlesinger et al., 1990), the Solar

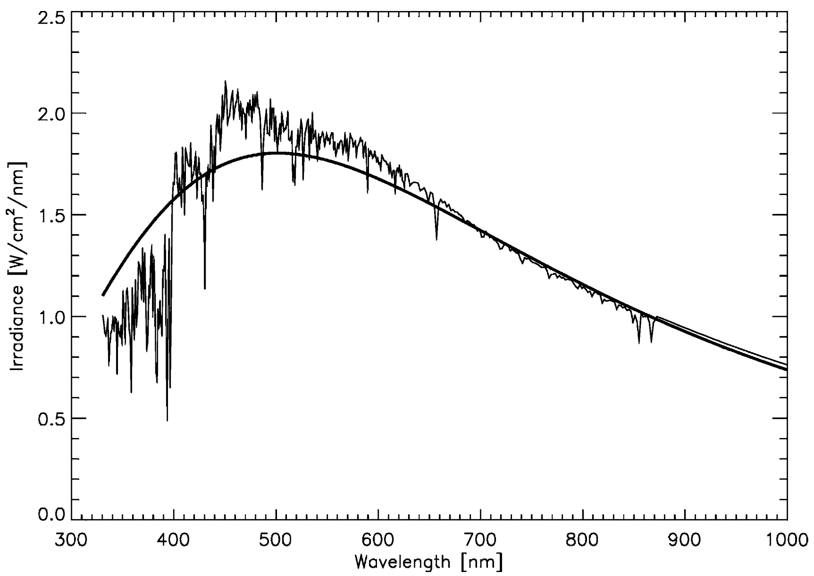

Fig. 1. The solar irradiance spectrum from 300 to 1000nm as measured by Labs and Neckel (1962) and corrected by Neckel and Labs (1984). It roughly follows a black body radiation curve of 5777 K (thick line), particularly in the IR.

Backscatter UltraViolet instrument (SBUV, SBUV/2) onboard the Nimbus-7 (1978–1986; Hickey et al., 1988; Kyle et al., 1994) as well as its successor the Shuttle Solar Backscatter UltraViolet instrument (SSBUV; Cebula et al., 1994) onboard several Space Shuttle missions, measured solar irradiance in the range of 160–400 nm with a spectral resolution of 0.1 nm. Another instrument, the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM; Vanhoosier et al., 1988; Brueckner et al., 1993) flew repeatedly on the Space Shuttle and on the Upper Atmosphere Research Satellite (UARS). It measured solar irradiance between 115 and 410 nm with a spectral resolution varying from 0.15 to 5 nm. In addition to the SUSIM, the UARS also carries the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE) which measures solar UV irradiance between 118 and 425 nm (Rottman, 1988; Rottman et al., 1994; Rottman, 2000).

An instrument that also measured wavelengths longer than 400 nm is the Solar Spectral Measurement (SOLSPEC) experiment flown on all three missions of the Atmospheric Laboratory for Applications and Science (ATLAS; Thuillier et al., 1998). The three spectrometers of SOLSPEC monitor solar irradiance changes at UV (180–370 nm), VIS (350–900 nm) and IR (800–3000 nm) wavelength ranges, with a spectral resolution of 1 nm each.

2.1. Spectral irradiance variability

Records of relative solar irradiance changes obtained from space-borne instruments allow the examination of variations on time-scales of minutes up to the solar cycle. The rich spectrum of solar irradiance variability is the result of an interplay between different physical mechanisms acting on various time-scales. A considerable part of the variations over the solar cycle is thought to be caused by the longer-lived faculae and active network elements. Fig. 2 shows relative irradiance changes from activity minimum to maximum, as compiled by Lean (1997) and extrapolated to longer wavelengths by Lean (1991). For comparison, the dotted line marks the 0.1% variability level exhibited by the total solar irradiance. Most prominent is a dramatic increase of solar irradiance variations towards shorter wavelengths (note the logarithmic scale of the y-axis). As a result, solar UV radiation below 300 nm accounts for up to 14% of the total variation while contributing less than 1% to the value of total irradiance (Lean et al., 1997; Solanki and Unruh, 1998) only.

Many details of solar spectral irradiance variations are still missing. Most of the instruments have focused on the solar spectrum of length less than 400 nm, where the exhibited variations are much stronger than in the visible or infrared. Also, our knowledge of the spectral variations as a function of the activity cycle phase is incomplete since most time-series cover only a small part of a solar cycle.

A closer inspectation of the solar spectrum of length 400 nm still has to await future endeavors. The Solar Radiation and Climate Experiment (SORCE) to be launched in mid-2002 (Rottman, 2000) is very promising. It consists of several irradiance experiments. Among them is SIM, a spectral irradiance monitor which will carry out measurements between 200 and 2000 nm with varying resolution from 1 to 34 nm and an absolute and relative accuracy of 0.03% and 0.01%, respectively.

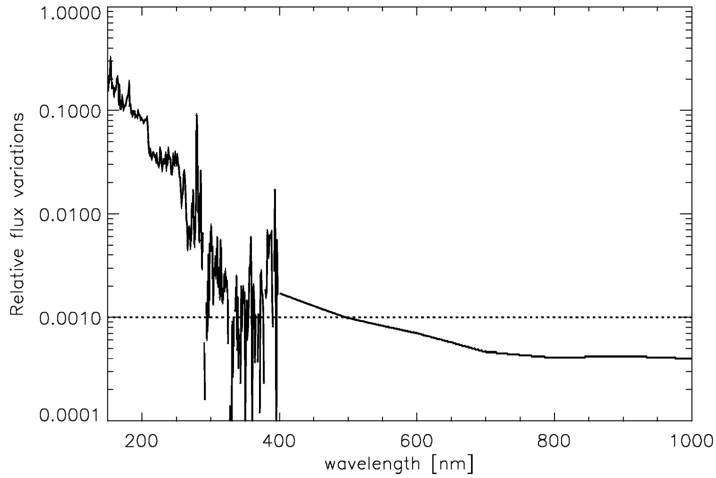

Fig. 2. Relative irradiance variations between solar activity minimum and maximum. The solid line represents calculated values as compiled by Lean et al. (1997) and extrapolated to longer wavelength by Lean (1991). Most prominent is a strong increase of solar spectral irradiance variability towards shorter wavelengths. The dotted line marks the variability exhibited by the total solar irradiance. Note the logarithmic plot. The variations in the UV are orders of magnitude larger than in the visible.

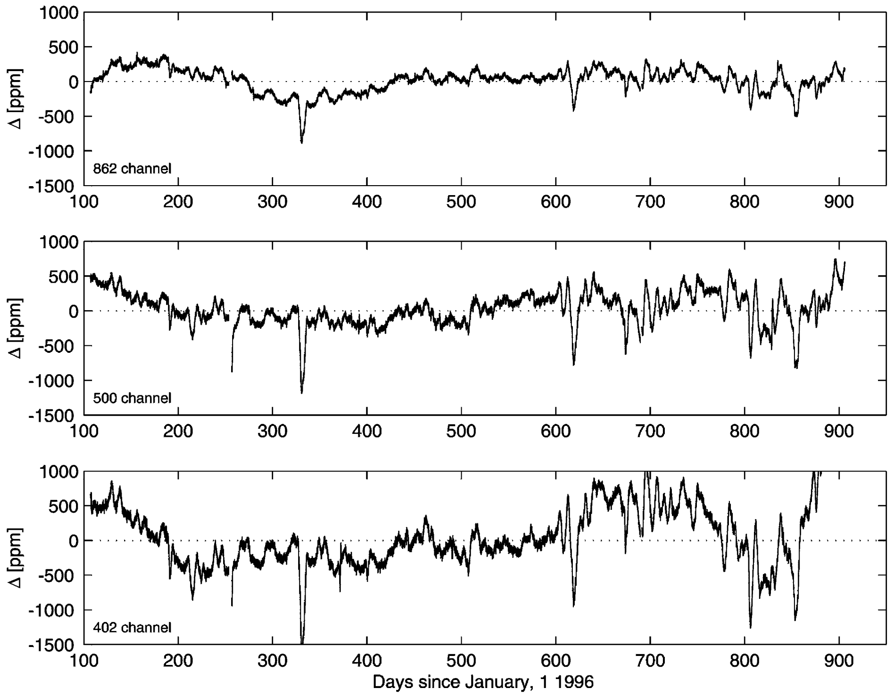

Fig. 3. Time-series of the three channels of the SPMs of VIRGO. Although the three channels show a similar short-term behavior a detailed examination shows significant differences.

Until now, however, the only instrument which measures relative solar irradiance changes at visible and infrared wavelengths is the Variability of Irradiance and Gravity Oscillation experiment (VIRGO) onboard Solar and Heliospheric Observatory (SOHO).

2.2. Short-term variability

VIRGO consists of two 3-channel sunphotometers (SPM) which measure relative irradiance changes at 402 nm (blue channel), 500 nm (green channel) and 862 nm (red channel)

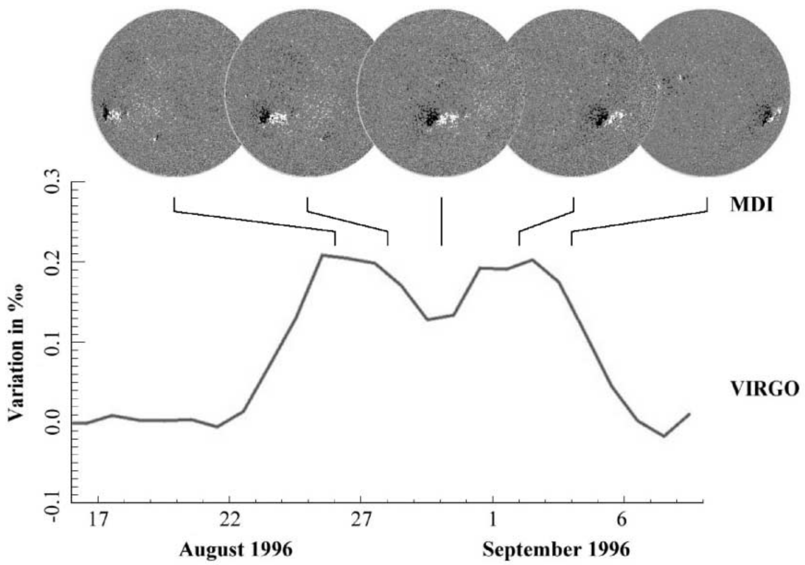

Fig. 4. Time-series of solar total irradiance variations recorded by VIRGO between August and September 1996 during the passage of a faculae-dominated active region across the solar disk. On top are the MDI magnetograms illustrating the passage of the active region from the solar eastern to the western limb. The variation exhibited by the irradiance record is determined by the pronounced CLV of the facular brightness.

with a bandwidth of 5 nm each. The high temporal resolution (1 measurement per minute) and sensitivity (precision better than 0.01% for relative irradiance values) offers a unique possibility to study the influence of active regions on solar irradiance at different wavelengths. Fig. 3 shows time-series of spectral irradiance variations measured by the SPMs for approximately the first two years of operation. The three time-series show quite a different behavior, with the strongest variations being in the blue channel. The comparison of time-series at different wavelengths and on various time-scales helps to achieve a better understanding of the physical nature of the origin of these variations.

As an example, Fig. 4 shows a faculae-dominated active region harboring a small sunspot as it crossed the solar disk between August and September 1996. The magnetograms on the top are taken by the Michelson doppler imager (MDI) onboard SOHO and illustrate the passage of the active region from the eastern to the western solar limb. Below are the variations of the total solar irradiance simultaneously recorded by VIRGO. The center-to-limb variation (CLV) of the facular brightness causes a double peak in the irradiance record due to the reduced contrast of faculae near disk center.

3. Interpretation

The different time-scales found in solar irradiance time-series are related to different physical mechanisms. While the origin of the short-term variations (days to weeks) is mainly attributed to the changing emission of active regions as they evolve and move across the solar disk, the origin of the long-term contribution that causes the 11-year cycle-to-cycle variability is still debated. Only models that allow irradiance variations to be reconstructed on a variety of time-scales can provide a more complete and comprehensive answer to this open question.

Many attempts to construct such models can be found in the literature (Lean et al., 1995, 1998, Foukal and Lean, 1986, 1988, 1990; Hoyt and Schatten, 1993, 1998, 1999). The majority of these models assume that solar irradiance

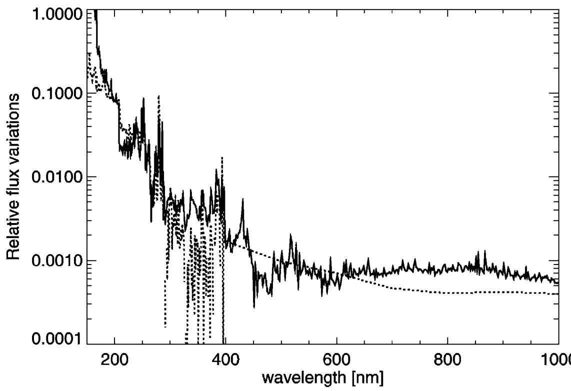

Fig. 5. Relative solar irradiance variations between activity minimum and maximum (dotted line; Lean, 1991, 1997) and the reconstruction according to the 3-component model of Unruh et al. (1999) based on calculated facular and sunspot contrasts as a function of wavelengths (solid line; From Unruh et al., 1999).

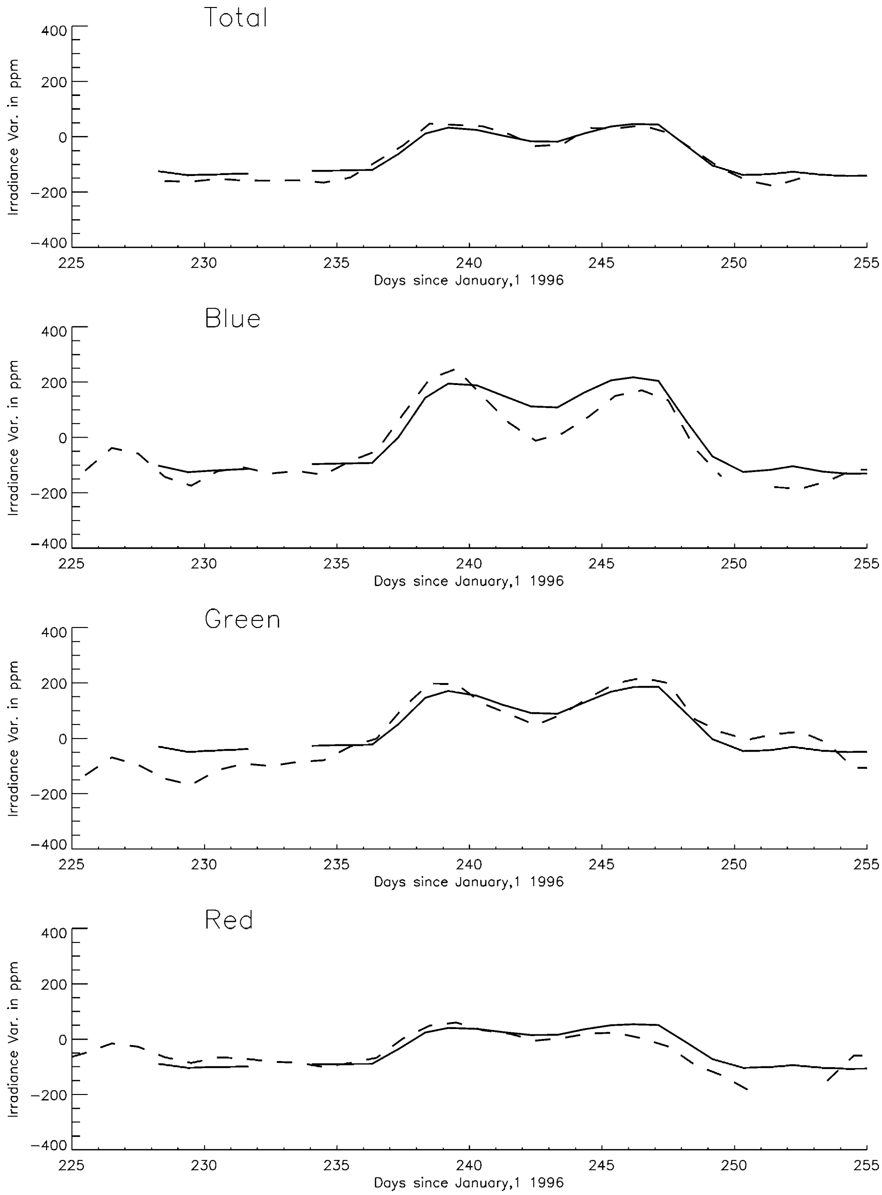

Fig. 6. Short-term variations of solar total and spectral irradiance as measured by VIRGO (dashed) between mid-August and mid-September during the passage of a faculae-dominated active region. The reconstructed time-series (thick lines) follow the observations rather closely, although some deviations remain unexplained (from Fligge et al., 2000).

changes are caused by surface magnetic features, at least on the time-scales accessible by modern irradiance measurements. These models can be divided into two categories. Firstly, there are models based on a correlation analysis between observed irradiance changes and indicators (proxies) of solar magnetic activity (Foukal and Lean, 1990; Lean et al., 1995; Solanki and Fligge, 1998, 1999). Since they make use of a variety of different proxy data sets that extend further back in time, these models are able to reproduce irradiance back in time as well. While this is necessary in order to estimate the influence, the solar irradiance changes on the terrestrial climate system; they do not, however, lead to a deeper understanding of the physics that drives solar irradiance variations.

The second category of models takes a different, more physically based approach. Starting from basic atmospheric models for each of the various components distinguishable on the solar disk the total or spectral intensity (or flux) of each component is computed. Irradiance variations are then modeled according to the varying surface distribution of the individual components over the solar disk (Fontenla et al., 1999; Fligge et al., 2000). The basic free parameters of these models are the input model atmospheres for the individual components, i.e., in particular their temperature stratifications.

Finally, other mechanisms of non-magnetic origin or whose connection to solar surface magnetism is only indirect have also been proposed as a substantial driver of solar irradiance changes (Kuhn et al., 1988; Kuhn and Libbrecht, 1991; Sofia, 1998).

In the discussion that follows, we present a model based on changes of the solar surface magnetism, which is able to reproduce the major observations presented in Section 2. The model differentiates only between three different solar surface elements, namely sunspots, faculae and the quiet Sun which is supposed to be time-invariant. The quiet Sun corresponds to Kurucz's solar model atmosphere (Kurucz, 1992a, b, c) of 5771 K, while the sunspot contribution is calculated from a model atmosphere of 5150 K, which in turn is interpolated from Kurucz's grid of model atmospheres. The facular model atmosphere is similar to model P of Fontenla et al. (1993) but has been slightly modified to reproduce better the VIRGO observations (Unruh et al., 1999). From these models, intensity spectra as a function of the limb angle μ are calculated using Kurucz' spectral synthesis code (ATLAS).

Fig. 5 shows the relative flux variations between solar activity minimum and maximum as reproduced by this model (solid line). The dotted line is again the compilation from different calculations by Lean (1991, 1997). The total area of the solar disk covered by faculae relative to the one covered by sunspots during activity maximum was taken to be 10 (Unruh et al., 1999) which is, however, at the lower limit compared to the values derived by Chapman et al. (1997). The overall shape of the spectral variability is relatively well reproduced. However, the model overestimates the variability in the near UV between about 300 and 400 nm, possibly due to the assumption of strict LTE, whereas radiation from the upper photosphere often shows departures from this assumption. This problem becomes more pronounced at even shorter wavelengths (not shown in Fig. 5) where the NLTE approach of Fontenla et al. (1999) and Fox (2000) is to be preferred.

Taking into account the center-to-limb variation of the contrast of sunspots and faculae, short-term variations of solar irradiance can also be reproduced with high accuracy. For that, magnetic maps are created by decomposing magnetograms into sunspot and facular regions. Each pixel is then replaced by a corresponding intensity value that depends on the magnetic filling factor and position on the solar disk. Finally, by summing the intensities over the full solar disk, the value for the irradiance is obtained.

Fig. 6 shows such a calculation for the passage of a faculae-dominated region across the solar disk between mid-August and mid-September 1996. Plotted in the figure are the observed (thin line) and reconstructed (thick line) time-series for the total solar irradiance, as well as for the three channels of VIRGO. The model is able to reconstruct solar irradiance variations on time-scales of the solar rotation relatively well and can clearly reproduce the double-peaked structure originating from the CLV of facular brightening.

4. Conclusions

The discovery of a close relationship between the changes of solar magnetic activity and solar irradiance has reinforced the efforts to monitor solar total and spectral irradiances during the past years. Even more, the correlation between solar irradiance changes and various indicators of the Earth's climate system changes (Eddy et al., 1982; Friis-Christensen and Lassen, 1991; Beer et al., 1994; Haigh, 1996; Labitzke and Van Loon, 1997) has drawn the attention in solar irradiance changes to scientists outside the solar physics community.

Many details of the relation between solar irradiance, solar magnetism and terrestrial climate, however, are as yet unknown and future efforts are needed to obtain a deeper understanding of the underlying physics. Experiments have been proposed to monitor the full solar spectrum with high temporal and spectral resolution. These experiments, which carry on the long tradition of solar irradiance monitoring, hopefully will shed new light on many of the hidden aspects of this lively field of research.

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