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THE SIGNATURE OF SOLAR ACTIVITY IN THE INFRARED SPECTRAL IRRADIANCE

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ABSTRACT

The effects of solar activity on the spectral irradiance have been studied using atmospheric semiempirical models developed from observations of the various surface features observed on the Sun. From these models, it has been the long-standing belief that the contributions of active regions to solar irradiance at wavelengths in the range of 1.2–3 μm is negative; that is, their net effect reduces the overall solar irradiance at these wavelengths by a small amount. For verifying the validity of the current modeling, we use the observed plage areas to compute the solar irradiance variations at two bands (centered at 0.516 and 1.553 μm wavelength). We compare in detail the predictions of the models by Fontenla et al. with measurements of the solar spectral irradiance variations obtained by the Spectral Irradiance Monitor instrument aboard the *Solar Radiation and Climate Experiment* spacecraft. The data comparison extends over a 6 month period in 2003 that covers several solar rotations. The comparison indicates that the variations in the short wavelength display good agreement between models and observations but also that the current models of IR spectral irradiance are inaccurate at the long wavelength. This disagreement in the IR may be due to the fact that, contrary to the current model assumptions, the presence of active regions on the disk increases the spectral irradiance at all wavelengths, even near 1.6 μm. Consequently, the modeling of solar spectral irradiance at wavelengths in the range around 1.6 μm has to be revised to match the new observations.

Subject headings: solar-terrestrial relations — Sun: activity — Sun: atmosphere — Sun: infrared

1. INTRODUCTION

The effects of solar activity on the spectral irradiance have been modeled by several authors using detailed atmospheric models of features that are observed on the solar disk. For example, Solanki & Unruh (1998) and Fontenla et al. (1999) describe a method for computing solar irradiance variations from models constructed to match radiance observations of features of the quiet and active Sun. This Letter provides a detailed comparison of model and observations of irradiance for a time period of several months.[1] In modeling the spectral irradiance, individual spectra are calculated for each atmospheric model weighted by the feature area and location. The Fontenla et al. (1999) models and their predecessors (Maltby et al. 1986; Fontenla, Avrett, & Loeser 1990, 1991, 1993) assumed that plage and facula contributions to solar irradiance at wavelengths in the range 1.2–3 μm are negative, with a peak negative value around 1.6 μm; i.e., the presence of plages and faculae on the disk would reduce the overall solar irradiance at these wavelengths. Earlier models developed by other authors (e.g., Chapman 1977; Walton 1987; Solanki & Brigljevic 1992) are not based on infrared (IR) radiance observations, and we do not evaluate them in this Letter. Also, Unruh, Solanki, & Fligge (1999) discuss a modified version of the Fontenla et al. (1993) model, but also they do not include the IR-observed contrast. In addition, Solanki & Unruh (1998) computed a synthetic irradiance with modified versions of existing models, and their results show a neutral behavior in the IR region around 1.6 μm, but they remark that their model was not devised to account for the observed radiance contrast at these wavelengths.

Fontenla et al. (1993, 1999) atmospheric models of faculae and plages are based on measurements of a few active regions by Foukal et al. (1990), Moran, Foukal, & Rabin (1992), and related papers. These observations indicate that portions of the Ca II K plage regions are not bright but are actually dark at 1.63 μm. Fontenla et al. (1993, 1999) models assumed that the temperature structures corresponding to plages and faculae were consistent with the "dark faculae" as reported in Foukal et al. (1990) and Moran et al. (1992). However, Moran et al. (1992) did note that "much of the magnetized area outside of the sunspots in Figure 1 does not appear as dark faculae in the 1.63 μm image." Consequently, assigning a decreased temperature to the entire plage and facula areas derived from Ca II K images was perhaps an overinterpretation of the spatially resolved observations.

In this Letter, we compare the solar irradiance variations, estimated using the solar disk decomposition and models from Fontenla et al. (1999), with current measurements of the solar spectral irradiance taken during several solar rotation periods of the present solar cycle. The comparison is carried out for two narrow bands—one at visible wavelengths and one in the IR near 1.6 μm. These new measurements were obtained by the Spectral Irradiance Monitor (SIM; Harder et al. 2000) instrument aboard the *Solar Radiation and Climate Experiment* (*SORCE*) spacecraft (Woods et al. 2000), and they are the first observations in the IR with sufficient precision to determine true solar variations.

2. SOLAR ATMOSPHERIC MODELS

Fontenla et al. (1999) describe a method for synthesizing the solar irradiance spectrum from ground-based imaging observations. Spectra are computed for a set of seven atmospheric models weighted by the area and location of the corresponding features on the solar disk. The various atmospheric models correspond to the observed solar features, including three models for the quiet Sun (model A for dim intranetwork, model C for average intranetwork cells, and model E for network lanes), three models for solar active regions (model H for average plage, model P for bright plage, and model S for sunspots), and one model for the bright enhanced network resulting from the decay of active regions (model F).

[1] See http://lasp.colorado.edu/pspt.

These models use an arbitrary zero height point chosen at the level of the solar atmosphere where the optical depth at 0.5 μm is unity at disk center. The range of heights near zero is referred to as the solar photosphere and produces the emitted visible continuum radiation. Emerging continuum radiation at wavelengths longer than about 0.8 μm is produced in layers deeper than zero height. However, this is valid only up to about 1.6 μm, which corresponds to the minimum absorption coefficient of H^- and the deepest directly observable layer (Fontenla et al. 1999). At still longer wavelengths than 1.6 μm, the radiation originates in progressively higher layers, reaching the chromosphere at millimeter wavelengths in part because of an increasing H^- free-free opacity. Thus, the IR continuum at 1.6 μm is produced at the deepest layers of the solar photosphere almost 100 km below the zero height at disk center, a level believed to be close to the top of the solar convective layer.

The current models for the different features of the quiet Sun (models A, C, and E) are identical at all depths in the solar atmosphere below the zero height (Fontenla et al. 1999). Likewise, model F is identical to these quiet-Sun models below zero height. However, all models of active region features (models H, P, and S) have a decreased temperature at negative heights (positive depths) compared with the quiet-Sun models at the same height.

For the sunspot model, the temperature values were selected to produce emerging intensities consistent with many observations showing that sunspots are dark at all wavelengths. However, for plages or faculae, the decreased temperature resulted from the report by Foukal et al. (1990), and related work, which showed dark faculae at 1.63 μm. However, Moran et al. (1992) also show that only certain portions of the Ca II K plage regions are dark, mainly regions close to the sunspots, while other regions are not dark. Their paper asserts that much of the magnetized area outside sunspots does not appear as dark faculae in 1.63 μm and describes a statistical relationship with magnetic flux.

The more recent papers by Sobotka et al. (2000) and Sanchez Cuberes et al. (2002) confirm these dark plage observations and our plage models for the most part. Sanchez Cuberes et al. (2002) describe the center-to-limb variation (CLV) observed in an active region at 1.55 μm and compares it with the CLV observed at 0.8 μm. The Figure 6 in Sanchez Cuberes et al. (2002) displays a negative facular contrast at 1.55 μm of about 2% that extends from disk center to about $\mu = 0.55$, and our Figure 1 shows the corresponding contrast produced by the Fontenla et al. (1999) model P. The main difference between the model and observed CLV is that the observed contrast with respect to the quiet Sun peaks at about $\mu = 0.3$ and then decreases to negative values again, while the model contrast continues to increase to the very edge of the disk. This turnover of the contrast in the CLV observations is hard to explain with simple plane-parallel models such as those of Fontenla et al. (1999). Reproducing the CLV observations may require "hot wall" models, which at this point are speculative and hard to evaluate. In any case, the decreasing contrast at the very limb of the Sun is not expected to have a major effect because, as Unruh et al. (1999) note, "the flux contribution beyond $\mu = 0.2$ is very small," and would not solve the issue that arises in comparing the observed and modeled solar irradiance.

In Figure 1, we show the CLV computed from the model P normalized to a reference according to the following formula:

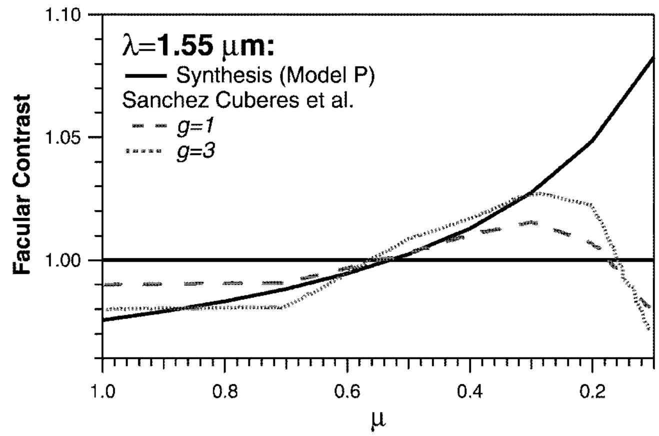

FIG. 1.—IR CLV for model P compared with model C (*solid line*). The dashed and dotted curves are from Sanchez Cubres et al. (2002).

$$V = \frac{I - I_{\text{ref}}}{I_{\text{ref}}}, \tag{1}$$

where I is the intensity and I_{ref} is the selected reference. The reference used in Figure 1 is the intensity at the same value of μ for model C that represents the quiet Sun. This CLV was computed for the 1.553 μm band observed by SIM and is dominated by the continuum.

In this Letter, we use the Fontenla et al. (1999) models and methods in order to construct the solar spectral irradiance integrated over two narrow wavelength bands. To establish the area and location of the solar features, we use the Ca II K images obtained by the Precision Solar Photometric Telescope (PSPT; see Coultrer, Kuhn, & Lin 1996 and White et al. 2000), and we take into consideration not only the area of the feature but also its location on the solar disk. We use the decomposition into annuli described by Fontenla et al. (1999) to account for the CLV for each wavelength band.

3. SIM OBSERVATIONS COMPARISON

In this Letter, we use the first accurate solar spectral irradiance measurements in the visible and IR carried out in the period from 2003 March to August 2003 the SIM instrument aboard the *SORCE* spacecraft. Although these preliminary data are not yet fully corrected for instrumental and observational effects, they are adequate to infer the irradiance variability during solar rotation intervals with strong modulation, such as those during the months of 2003 June and August.

We analyze two wavelength bands, 0.516 μm in the visible range and 1.563 μm in the near-IR. These two bands correspond to a triangular bandpass with an FWHM of 0.021 and 0.024 μm, respectively. Here we consider a time period of a single solar rotation during the month of June that displays one of the largest irradiance variations during the early part of 2003. During this period, there is nearly complete SIM and PSPT data allowing a day-by-day comparison of observation and modeled irradiance. The modeled spectra are convolved with a triangular response function with the widths mentioned above in order to match the SIM instrument profile.

The locations and areas of the solar features corresponding

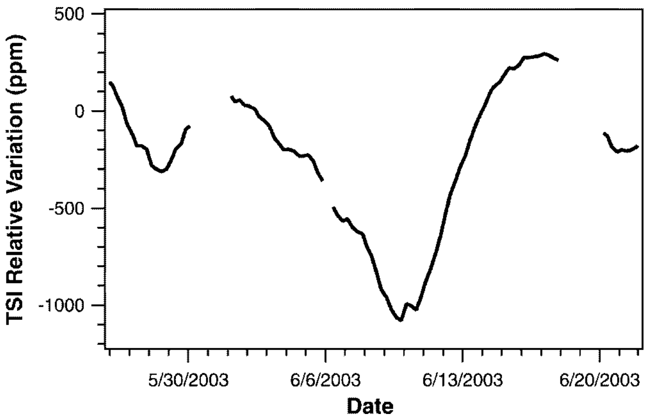

FIG. 2.—Observed TSI variation during the solar rotation in 2003 June. The variation is relative to the level on 2003 May 31.

to each model during these days were identified in the PSPT Ca II K and red continuum images by decomposing the solar disk according to the seven features of the models. The areas of the active region features H and P may be somewhat affected by the broad band of the PSPT filter (~0.25 nm) that includes not only the Ca II K line center but also a portion of the wings. The sunspot areas and positions are obtained from the red filter at 0.65 μm, and these areas do not include the penumbrae. (A drawback of the current modeling is that no atmospheric models yet describe the penumbrae; by default, model A is currently assigned to it.)

Figure 2 shows the total solar irradiance (TSI) variation as provided by the *SORCE* Total Irradiance Monitor (TIM) computed using equation (1) and using the value at May 31 for reference. The TSI pattern shows the large sunspot area crossing the disk that produces a local minimum in irradiance corresponding to the maximum projected sunspot area and the irradiance increase as the active region areas approach the limb.

In Figure 3, we compare the SIM data with the model data for the two spectral bands. The relative irradiance variations in Figure 3 are computed again according to equation (1), but with I representing the spectral irradiance and $I_{\rm ref}$ the available reference level. Since quiet-Sun irradiance is not yet observed, again the reference level was chosen to be that on May 31. We stress that both the area of the features and their location on the disk are important because of their CLV (e.g., in the visible, faculae have zero contrast at disk center but turn brighter as they approach the limb). This CLV of each of the features is properly accounted for by the Fontenla et al. (1999) spectral irradiance synthesis method.

The top panel of Figure 3 shows the computed and observed variation at the 0.516 μm visible spectral band as a function of time, and the bottom panel of Figure 3 shows the 1.553 μm IR spectral band. The two wavelengths of the SIM data basically show the same characteristics as the TSI after the time of minimum irradiance, although the 0.516 μm band has a larger amplitude and a slower decrease before the minimum. The visible shows this slow decrease because in this particular case, the sunspot is leading the plage within the active region, and the brightening of the trailing plage somewhat cancels the darkening of the sunspot as the two move onto the solar disk. After the irradiance minimum, these two effects reverse, and the sunspot deficit is removed while the plage brightness continues to increase, giving rise to the second larger peak in irradiance.

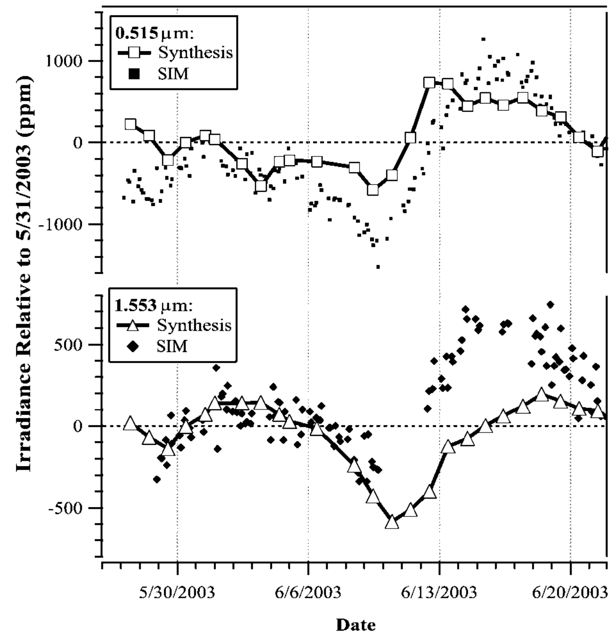

FIG. 3.—Modeled and observed solar irradiance variations during 2003 June. The variations are relative to the levels on 2003 May 31, and the zero line is shown for reference.

The observed visible band shows the same qualitative behavior but a larger decrease than the modeling results because of the presence of sunspot penumbrae. Our modeling does not yet have a penumbra model to assign, and model A certainly overestimates the irradiance from penumbra areas. Also, small pores can escape detection in the images, depending on the highly variable image quality and scattered light, and may be assigned model A or model C depending on their size. Thus, the current synthesis underestimates the effects of penumbrae and pores, and this affects the depth of the minimum, and probably somewhat the reference level used, because isolated high-quality images display extensive penumbrae of these "delta sunspot groups" as well as a number of small pores around the main spots.

Figure 3 also shows that the model calculations at the 1.563 μm band do not behave like the observations after the sunspot minimum, because the observed maximum is not reproduced by the modeling. Again we stress that our modeling is taking into account the facular contrast and CLV consistent with published values, and thus this disagreement is not due to incorrect models but reflects a not yet understood effect.

There is considerable noise in the synthesis data because of an inadequate determination of the areas and positions of features, the sparseness of the PSPT data, and intrinsic problems of image quality. Also, the yet unrefined noise of the SIM data produces scatter in the observations. Consequently, the values in the figure should not be regarded as definitive but are used only to illustrate the trend in the models and the observations. Despite the noise, it is clear that the synthesis at 1.553 μm does not reproduce the observed behavior. More studies are in progress that will further reduce the noise of the SIM-processed data, and as the solar minimum approaches a better reference value for the quiet Sun, irradiance will be established.

The observed IR irradiance variation tracks the variation in TSI, and in fact even better than the visible variation in many details, but the amplitude of the variations is larger at 0.516 μm than at 1.553 μm. A similar pattern is displayed by other solar rotations during the 2003 March–August time frame and at other wavelengths in the visible and IR. We conclude that the differences between the model and the observations shown in Figure 3 are not an isolated event but are very common for most active regions.

4. CONCLUSIONS

Present estimates of irradiance variability have been based on the assumption that most, or all, plage regions appear dark at 1.6 μm. Consequently, modelers predict that at solar maximum, the irradiance at wavelengths around 1.6 μm is decreased with respect to the quiet-Sun value. These calculations were based on the Fontenla et al. (1999) models, or earlier and similar models, which have a decreased temperature with respect to the quiet Sun at heights below the arbitrary zero reference height for the faculae and plage features and reproduce the observed facular CLV up to about $\mu = 0.3$. Other calculations, like those used by Solanki & Unruh (1998), predict basically zero contrast at IR wavelengths, but they use facula models that are not consistent with CLV observations of facular contrast (e.g., Moran et al. 1992; Sanchez Cuberes et al. 2002). Yet other models (e.g., Walton 1987) may explain the observed maxima in the IR facular contrast by resorting to "hot wall" and "flux tubes," but so far they have several undetermined parameters, and they lack adequate treatment of the MHD, energy balance, and radiative transfer that is expected in such complex geometries. In any case, the prediction of IR variability by flux-tube models still needs to be assessed, but it seems unlikely that it will provide results with different qualitative behavior from the plane-parallel models near 1.6 μm.

The new observational data confirm that the irradiance variations at visible wavelengths make the Sun's color a bit bluer when active regions are present on the solar disk because the shorter wavelengths vary more than the longer visible wavelengths. However, we find unexpected enhanced spectral irradiances at IR wavelengths, near the minimum H^- opacity, due to the passage of active regions. We have also studied other wavelengths in the visible and IR that display the same basic behavior. The TSI variations exhibit a mix of features from both the visible and IR spectral ranges and, in some respects, seem closer to the IR.

We conclude that the recent SIM observations show that model predictions of IR irradiance variations are incorrect and, consequently, that the models need to be changed and that solar variability estimates for the IR should be revised accordingly. The assumption that all faculae and plages are dark needs to be carefully examined by relating the brightness at various wavelengths with the magnetic field vector strength and orientation with respect to the solar radius. We stress that most plage and facular areas display strong horizontal fields, often larger than the vertical fields, and in these conditions, models of vertical flux tubes cannot adequately describe the physics involved. Indeed, a sophisticated analysis of MHD with radiative transfer in the photosphere under the presence of complex magnetic fields is still a challenge but would be very useful for understanding active regions.

A possible explanation for the observed irradiance near 1.6 μm is that some areas within plages and faculae may be warmer than the average quiet Sun in the deep photosphere, and if they overpower the dark faculae, they may produce a net increase in IR irradiance. This explanation and the intrinsic difficulty in setting an accurate photometric reference in high-resolution solar images can explain both the observations of dark faculae and also the IR irradiance variations after the sunspot minima. Alternatively, it is possible that around active regions, an extended but very low contrast region bright in the IR (with respect to the quiet Sun) could produce the observed IR irradiance enhancement. This explanation has the advantage that it could also explain the local maxima just before the sunspot minimum by a region that may not share all the spatial location of the plage.

Physical explanations for an IR enhancement, considering the dispersion of the heat flux blocked by the sunspots, are possible and may rest on the energy transport by radiation and upflows that are often displayed in the less magnetized portions of active regions. In any case, more work needs to be done in both the observation and modeling of active regions in the deep photosphere, and we expect that SIM observations will make a significant contribution in this regard.

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