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Understanding the Role of Small-Scale Flux in Solar Spectral Irradiance Variation

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Abstract. Global solar spectral irradiance variations depend on changes in magnetic flux concentrations at the smallest scales. Modeling has focused on the contributions of magnetic structures in full disk images as those contributions have strong center-to-limb dependencies, but these dependencies have never been determined radiometrically; only the photometric intensity relative to some reference 'quiet-sun', the magnetic structure contrast, is measurable with ground based imagery. This is problematic because unresolved inhomogeneities influence not only the full-disk structure intensities themselves, but also the quiet-sun background against which their contrast is measured. We thus argue that, to understand the physical causes underlying solar spectral irradiance variations, two fundamental questions must be addressed: What is the real $I_\lambda(B)$ as a function of $B$ in full-disk images? This can only be answered by imaging the Sun radiometrically from space, and we propose a Radiometric Solar Imager design. What governs spectral irradiance changes at sub arc-second scales? This can be addressed by a combination of high resolution ground based imaging (ATST-VBI) and three dimensional radiative magnetohydrodynamic modeling, and we propose a synoptic approach. Finally, a way to account for the variance introduced by unresolved substructure in spectral irradiance modeling must be devised. This is critical, as imaging and modeling at the highest resolutions but over the full solar disk will likely remain unattainable for some time.

1. Motivation

An important incomplete component in our understanding of the causes of the Earth’s climate variability is the description of the Sun’s role. While it is clear that the Sun made only a small contribution to late twentieth century global climate change,\textsuperscript{2} the signature of solar cycle variations in global and regional climate are now quite well es-

\textsuperscript{1}‘Quiet-sun’ in this paper refers to the internetwork which, in irradiance studies, is typically identified as those regions of low emission in Ca ii K images. Quiet-sun, as used here, should not be confused with the broader non-coronal-hole-region usage found in discussions of chromospheric, transition region, or coronal emission.

\textsuperscript{2}The solar contribution to the global average increase in radiative forcing between 1750 and 2005 is 7.5% that of the anthropogenic contribution, with some uncertainty in the estimate. If one takes the extreme values of the two contributions over their individual 5 to 95% uncertainty ranges, the solar contribution lies between 2.4% to 50% that of the anthropogenic (IPCC Core Writing Team 2007).
tablished (Gray et al. 2010). It is yet unclear how this occurs. That uncertainty has been brought into sharp focus by spectral irradiance observations spanning the recent deep solar minimum which show opposite trends in the infrared and ultraviolet output of the Sun, with the former increasing into solar minimum while the later decreases (Harder et al. 2009). As a consequence, there is a predicted, but as of yet only poorly understood, phase difference between proposed bottom-up air-sea long-wavelength (Meehl et al. 2003; van Loon et al. 2004; Meehl et al. 2008) and top-down stratospheric-ozone short-wavelength (Haigh 1996; Shindell et al. 1999; Kodera & Kuroda 2002) Sun-climate coupling mechanisms. This phase difference may be of significant diagnostic importance, and elucidating the origin, evolution, and radiant output of solar magnetic features thus promises to simultaneously advance our understanding of the origins of solar variability and the workings of the terrestrial climate system.

2. Spectral irradiance observations

Observation of solar spectral irradiance have been made using the Spectral Irradiance Monitor (SIM) on the Solar Radiation and Climate Experiment (SORCE) spacecraft for more than seven years. The SIM measures the spectrum continuously from 200 to 2400 nm with a variable resolution of 1-30 nm using a single Fény prism over the entire spectral range and four different detectors. Instrumental sensitivity degradation has two primary causes (Harder et al. 2009, auxiliary materials). The most important is the exposure of the front prism surface to hard UV radiation. The degree to which this effects the measurements is determined by comparing the output of two identical instruments, SIM A and SIM B, housed in the same enclosure, so that they have the same physical, chemical, and thermal environments, but exposed to the Sun at different intervals, twice daily and monthly respectively. The second comes from non-exposure related contributions, predominantly energetic proton bombardment. This is assessed via inter-detector comparison, comparison between the photodiodes and the electrical substitution radiometer. It is important to note that degradation corrections for the SIM instrument are based on measured telemetry and no assumptions are made about the magnitude, slope, or time dependent behavior of the solar spectral irradiance. Analysis of the degradation trends demonstrates that the prism degradation, the largest single source of degradation, follows a Lambert (exponential) law caused by a wavelength dependent graying of the prism glass. It varies slowly and smoothly with wavelength, while the sign of the observed solar irradiance trend is observed to change abruptly over narrow regions of the spectrum lying on a common detector. After degradation correction over the full instrument operation range, the integrated SIM spectra from 200-2429 nm amounts to 97.3% of the TSI, with the 36.32 Wm$^{-2}$ deficit arising mostly from the unmeasured infrared portion of the spectrum. Ignoring the unmeasured portion of the spectrum, the fractional difference between integrated SIM and the TSI is about 150 parts per million (i.e. they agree to 0.015%). The integrated SIM and SORCE TIM irradiance time series are shown in Figure 1a.

The Sun’s radiative output (as measured at Earth) varies over the solar cycle with a phase and amplitude that depends critically on wavelength (Harder et al. 2009). Figure 1 plots SIM time series at the wavelengths near the peaks of the Precision Solar Photometric Telescope (PSPT) filters, with broader passbands than those of the PSPT since the SIM is a low resolution prism spectrometer. PSPT images play an important role in irradiance modeling (Section 3). Figure 1b plots cycle variations in the Ca ii K
Figure 1. Solar spectral irradiance as a function of time for specific wavelength bands. The phases and amplitudes of the solar cycle variations depend significantly on wavelength. The integrated spectral irradiance agrees well with the total (panel a).
3. Irradiance modeling difficulties

The appearance and disappearance of magnetic structures is known to account for most of the variation in total solar irradiance observed over the course of a solar cycle. Sunspots and pores have negative contrast against the background disk, while smaller scale magnetic fields generally contribute positively. Changes in both the fractional area covered and the disk location of these magnetic structures modulates the solar output, and a two component model based on a sunspot deficit (from observed areas and locations) and a facular excess (derived either from chromospheric proxies or observed facular area) can account for \( \sim 77\% \) of the observed total solar irradiance variation (e.g. Fröhlich & Lean 2004). The magnitude and even the sign of the contribution of any given magnetic structure, however, depends critically on the wavelength being observed as well as its disk position, and fits to spectral variability are consequently less compelling, particularly at long wavelengths.

Spectral irradiance trends are typically modeled empirically using multi-component decomposition of solar images and one-dimensional atmospheric models of each component (e.g. Fontenla et al. 1999). Full disk photometric images are decomposed into 7 magnetic feature types based on pixel contrast as a function of disk position. Figure 2 shows how the fractional area of these structures varies with solar cycle in the photometric images of the PSPT. Network and plage elements are identified by their contrast in Ca II K images (393.415 nm, 0.273 FWHM) while sunspot umbral and penumbral pixels are tagged based on their contrast in the red continuum (607.095 nm, 0.458 FWHM). The exact magnetic structure definitions employed follow the semi-empirical center-to-limb corrected thresholding scheme of Fontenla et al. (1999), and for the PSPT images can be found in any mask image header downloadable from the data service website http://lasp.colorado.edu/pspt_access/. Once the structures are identified, one-dimensional atmospheric models of their thermodynamic state are used to calculate the emergent intensity as a function of disk position and with 1 Å spectral resolution. Summing over all pixel contributions yields the model’s integrated spectral irradiance which can be compared to observations.

Based on measured changes in the fractional area and disk position of magnetic structures, such models are able to reproduce the observed solar rotational modulation quite well, as well as long term trends at short wavelengths (UV irradiance changes with solar cycle). They have more difficulty reproducing long term trends at long wavelengths without invoking thermodynamic changes in the ‘quiet-sun’ (internetwork). Since most of the solar disk (70-80\%) is identified by the structure contrast scheme as internetwork, such inferred changes can be very small and yet have dramatic effects on the solar spectral irradiance, but their physical origin is unclear. The solar atmosphere is anything but static, and much of this dynamics occurs on sub-pixel scales in full disk images. Moreover, the ‘quiet-sun’ is not completely quiet and thus the unresolved magnetic substructure of the internetwork likely changes with the cycle. These impact the irradiance modeling in at least two ways. The background state against which magnetic structure types are defined changes with cycle. A subtle change the internetwork center-to-limb profile with cycle would systematically change the magnetic component identifications since they are based on contrast measures. Additionally, unknown vari-
Figure 2. Fractional solar disk area $n$ covered by magnetic structures of type indicated by the panel labels as function of time (calendar years). Bold symbols plot the running 13.5-day average values. The date of minimum unsigned flux in SOHO MDI images is indicated by a fiducial red vertical dashed line in late 2008. A period of very low activity and irregular spatially-dispersed small-scale magnetic flux emergence (Rast 2010) is marked by two vertical dashed lines in early 2009.

ance in the contribution of the internetwork to the solar spectral irradiance is introduced. Even in highly simplified models, the radiative properties of the atmosphere depend on the unresolved magnetic substructure, on the way the flux is distributed at smallest scales (Criscuoli & Rast 2009), and two-dimensional averages of a three-dimensional magnetohydrodynamic model atmospheres, at constant height or optical depth, do not produce an one-dimensional atmospheres with the same emergent intensity as the mean spectrum of the inhomogeneous atmosphere (Uitenbroek & Criscuoli 2011). This problem is common to all magnetic components identified in full disk imagery, not just the internetwork. Unknown changes in the underlying inhomogeneity affects the emergent intensity in ways difficult to model with a limited set of one-dimensional atmospheres.
Figure 3. Fraction of plage and facular pixels showing negative red $f_R$ or blue $f_B$ continuum contrast as a function of time (calendar years). Bold symbols plot the running 13.5-day average values. Vertical fiducial lines as in Figure 2. Horizontal red fiducial line set at an arbitrary value of 10%.

A good example of how these uncertainties can compound one another is the measured contrast of faculae and plage as a function of solar cycle. Not all full disk faculae and plage pixels, identified by their Ca II K contrast, show positive contrast in continuum intensity (Topka et al. 1997). Between 10 and 20% of the facular and plage pixels show negative continuum contrast, and this percentage varies with solar cycle (Figure 3). Though these ‘dark faculae’ tend to occur preferentially toward disk center, not all occur there and some are found quite far toward the solar limb where limb brightening is typically expected. Moreover, the dark faculae do not seem to be systematically associated with the strongest regions of magnetic flux density as deduced by Ca II K emission. They are found mixed with positive contrast pixels throughout a given active region. While further work is required to assess the nature of dark faculae and their contribution to spectral irradiance changes over the solar cycle, a fundamental observational difficulty underlies these results. Put starkly, we as yet have no ability to determine whether these cycle trends (or other variations observed) are due to changes in magnetic structures themselves, either their number densities and thus sub-pixel filling factor or thermodynamic structure, or to changes in the quiet-sun reference state, again either due variation in unresolved flux contributions or thermodynamic state. More likely, some combination of these contribute. The possibilities cannot be unambiguously untangled without absolute radiometric imaging of the full-disk and a statistical understanding of the unresolved contributions to full-disk pixel intensities.

4. Next steps in solar irradiance studies

While solar spectral modeling of global irradiance changes depend on contributions at the smallest scales, full disk imagery will always be required because disk position is critical to irradiance contributions. We thus argue that, to understand the physical causes underlying solar spectral irradiance variations, two questions must be addressed
Table 1. Possible wavelengths for full disk imaging with a Radiometric Solar Imager. (*) Uitenbroek and Criscuoli, in preparation.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>ID of</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>393.4 nm</td>
<td>Ca ii K</td>
<td>Historic record, core-to-wing ratio, magnetic structure identification</td>
</tr>
<tr>
<td>506.1 nm, 1241 nm</td>
<td>Pair 1</td>
<td>Opacity-conjugate wavelengths(*)</td>
</tr>
<tr>
<td>668.4 nm, 1055 nm</td>
<td>Pair 2</td>
<td>Opacity-conjugate wavelengths(*)</td>
</tr>
<tr>
<td>607.1 nm</td>
<td>PSPT Red</td>
<td>Continuum sample of anti-TSI trend, chromospheric dynamics</td>
</tr>
<tr>
<td>1083 nm</td>
<td>He ii</td>
<td>CLV for scattering polarization</td>
</tr>
<tr>
<td>1644 nm</td>
<td>Opacity minimum</td>
<td>Opacity minimum, deep photosphere</td>
</tr>
</tbody>
</table>

through observational and modeling efforts: What are the real center-to-limb intensity profiles of magnetic components in full disk images? Ideally these would be given by a set of functions covering all magnetic flux densities and wavelengths, but for practical reasons a component approach at select wavelengths may be more feasible. What governs spectral irradiance variance at sub arc-second scales? Can the differences between the spectrum of the mean one-dimensional atmosphere and the mean spectrum of the inhomogeneous atmosphere be described in terms of a distribution of contributions, so that rather than a single atmosphere being assigned to a each magnetic component a distribution of atmospheres is sampled to obtain any individual pixel’s contribution?

4.1. A Radiometric Solar Imager

While high-accuracy spacecraft measurements of the disk integrated total and spectral irradiance of the Sun have been ongoing for over 30 years, all precision irradiance imaging of the Sun to date has been photometric, not radiometric, measuring the relative intensities of pixels on the solar disk. By careful determination of the detector gain (flat-fielding) and the quiet-sun center-to-limb variation, the PSPT can achieve high precision (0.1%) relative photometry of the solar disk (e.g. Rast et al. 2008). There are, however, no measurements of the absolute radiometric intensity of the resolved Sun, and thus no assessment of the contributions of various magnetic structures to the disk integrated irradiance or of the radiometric center-to-limb profile of these structures from which to reconstruct those contributions. This means that all observations and all modeling efforts must define a ‘quiet-sun’ intensity, against which the contrast of the magnetic elements is determined. Since the quiet-sun brightness varies from disk center to the limb, and this profile is wavelength dependent, all contrast measurements and magnetic structure identifications are made relative to some arbitrary definition of the quiet-sun center-to-limb profile, and small differences in the observation passband or in the quiet-sun definition can result in center-to-limb profiles which vary significantly in both magnitude and sign (Ermolli et al. 2007, 2010, and reference therein).

We suggest that these difficulties can be overcome by developing a PSPT-like instrument with radiometric capabilities, a Radiometric Solar Imager (RSI). The effort would combine extant expertise in radiometry and imaging in an instrument capable of producing absolutely calibrated solar images at specific wavelengths (Table 1 summarizes possible filter bands). We envision the RSI to be two instruments in one package,
a photometric imager and pass band monitor combined with a high spectral resolution radiometer. Rather than calibrate and monitor the radiometric accuracy of the full imaging telescope, the idea is to normalize photometrically precise images by the integrated intensity that should have been observed through the filter passband to achieve an image over which the irradiance contribution of each pixel is known radiometrically.

The first component of such a system is a Photometric Imager and Pass Band Monitor (RSI-PIPB). It would acquire images of the Sun and profiles of the image passband with high photometric precision. Photometric imaging with 0.1% pixel to pixel relative precision requires careful detector gain determination which can be achieved via a Kuhn et al. (1991) like algorithm, as currently employed by the PSPT project. The spectral profile of the filter with similar photometric precision, could be obtained via a difference measurement, filter-in vs. filter-out, using an integrating sphere and spectrometer (Figure 4). So long as the flat mirror used to redirect the beam and the downstream components do not distort the shapes of the measured profiles, they would represent the spectral distribution of photons that reached the detector when the images were acquired. Determining the integrated area under those distributions, and thus the irradiance in the image passband, would be the task of the High Resolution Spectral Irradiance Monitor (RSI-HSIM). It is envisioned to operated over select frequency ranges with high spectral resolution and radiometric accuracy, so that the integrated intensity over the actual image pass band can be calculated. It is the component of the RSI that must be monitored carefully for degradation.

The final data product of the RSI would thus be a triplet consisting of a photometrically precise image, an associated photometrically precise filter profile, and a high-resolution radiometrically accurate measurement of the irradiance over a spectral region somewhat larger than the filter passband. Individually the first and third data items have intrinsic value, and the second would be used to integrate the passband and normalize the image to produce a radiometrically accurate measurement of the irradiance contribution of each full-disk pixel.

4.2. A synoptic strategy to understand unresolved irradiance contributions

What would remain unknown after such measurements is how sub-pixel inhomogeneities contribute to full-disk pixel intensities as a function of wavelength and disk posi-
tion. This can be addressed by a combination of high resolution ground based imaging (ATST-VBI) and three dimensional radiative magnetohydrodynamic modeling. The first could contribute a synoptic catalog of substructures underlying magnetic components in full disk images, while a large exploration of parameter space with the later would allow understanding of how the integrated intensity at differing wavelengths relates to that substructure, the mean field intensity, and viewing angle. Ultimately, but with no simple prescription, these underlying statistics must be accounted for in spectral irradiance modeling, as both imaging and three-dimensional dynamical modeling at the highest resolutions but also over the full solar disk (required by the strong center-to-limb dependencies) will likely remain unattainable for some time to come.

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