Irradiance Models Based on Solar Magnetic Fields

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A method to separate the active region and quiet network components of the magnetic fields in the photosphere is described and compared with the corresponding measurements of the He I λ 10830 absorption. The relation between the total He I absorption and total magnetic flux in active regions is roughly linear and differs between cycles 21 and 22. There appears to no relation between these two quantities in areas outside of active regions. The total He I absorption in the quiet Sun (comprised of network, filaments, and coronal holes) exceeds that in active regions at all times during the cycle. As a whole, active regions of cycle 22 appear to be less complex than the active regions of cycle 21, hinting at one possible cause for a differing relation between spectral-irradiance variations and the underlying magnetic flux for these two cycles.

1. Introduction

Variations of the radiative output of the Sun are directly linked to the short- and long-term evolution of the magnetic fields during a solar cycle. Understanding the spatial and temporal character of the solar magnetic fields is necessary in order to understand the thermal structures that ultimately result in the observed solar irradiance variations.

Visual examination of high-resolution, full-disk magnetograms of the photosphere show a myriad of structures that can be roughly described by three components: (1) active regions, (2) stronger network elements that are the dispersing remnants of active regions, and (3) relatively weak network elements that are distributed in a cell-like pattern over the entire solar surface. Several investigations (Lean *et al.* 1982; Skumanich *et al.*. 1984; Foukal & Lean 1988; Livingston *et al.* 1988; Schatten 1988; Willson & Hudson 1988; Foukal *et al.* 1991) indicate that these components of activity play important, but different, roles in the observed solar-irradiance variations.

For this study, magnetic flux structures are partitioned into two components: active regions and the quiet Sun. The quiet Sun component includes both the remnants of active regions and the weak magnetic network elements. These two components are considered in relation to spectral-irradiance variations in the He I λ10830 absorption. Described in Section 2 of this paper is the method used to isolate active regions from the quiet Sun magnetic fields. One additional parameter also is investigated, that is, the complexity of the magnetic fields. In Section 3, the total magnetic flux and its complexity in and outside these so-defined active regions are compared with the corresponding total He I λ10830 Å absorption in these two components.

2. Data

The National Solar Observatory/Kitt Peak (NSO/KP) synoptic rotation maps of the magnetic field and He I λ10830 spectroheliograms are used in this analysis. These rotation maps are constructed from the daily NSO/KP full-disk magnetograms; a description of the method used can be found in Gaizauskas *et al.* (1983) and Harvey (1992). The rotation maps shown in Figure 1 depict the distribution of magnetic flux and He I λ10830 structures during one complete rotation of the Sun, in this case Carrington Rotation 1712 (at the peak of magnetic activity in cycle 21, August 1981). Each equal-area pixel in the

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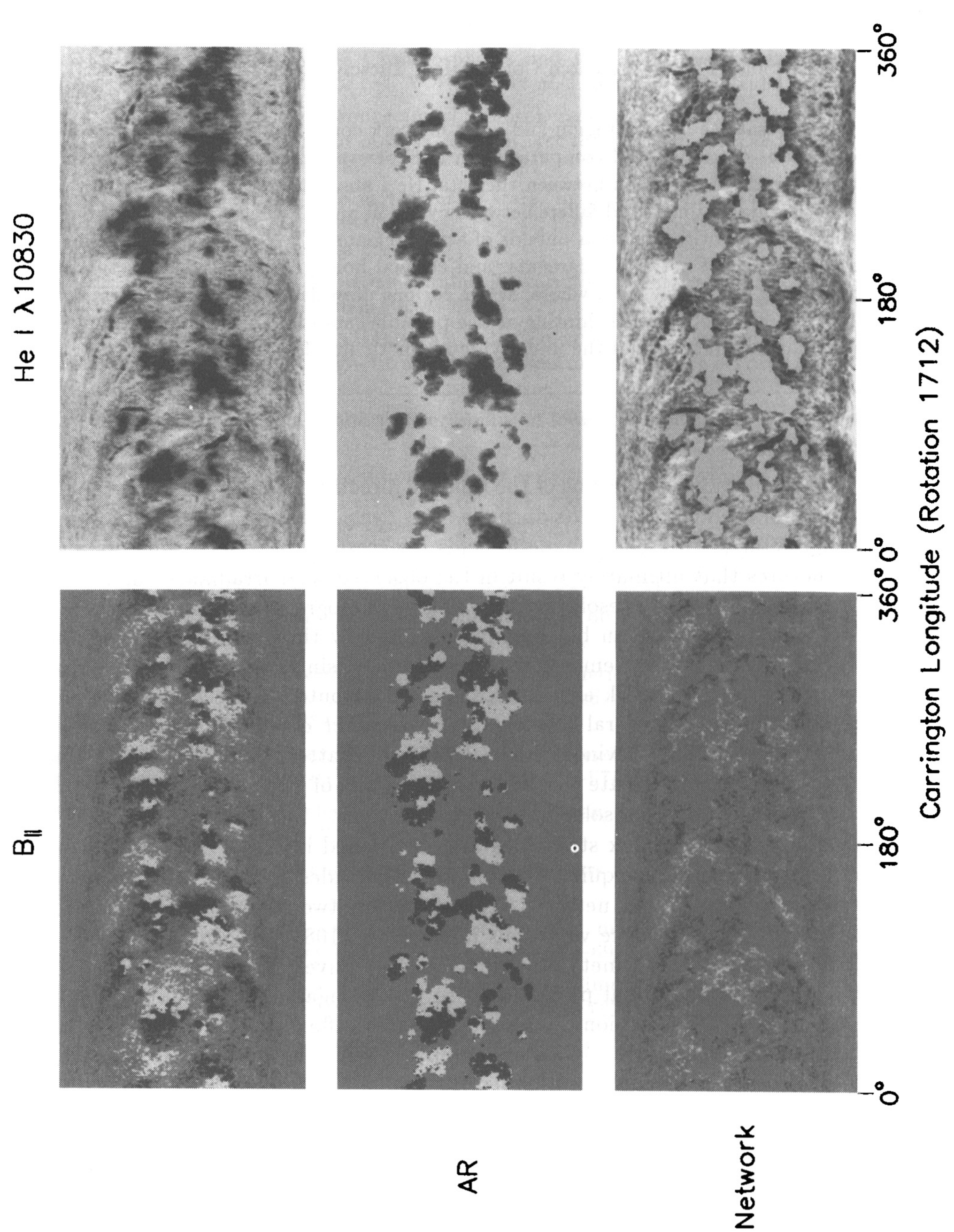

FIGURE 1. Synoptic rotation maps of the magnetic field *(left)* and He I λ10830 Å *(right)* for Carrington Rotation 1712. The *top* maps are separated into their active region *(middle)* and quiet network *(bottom)* components using the technique described in Section 2.1.

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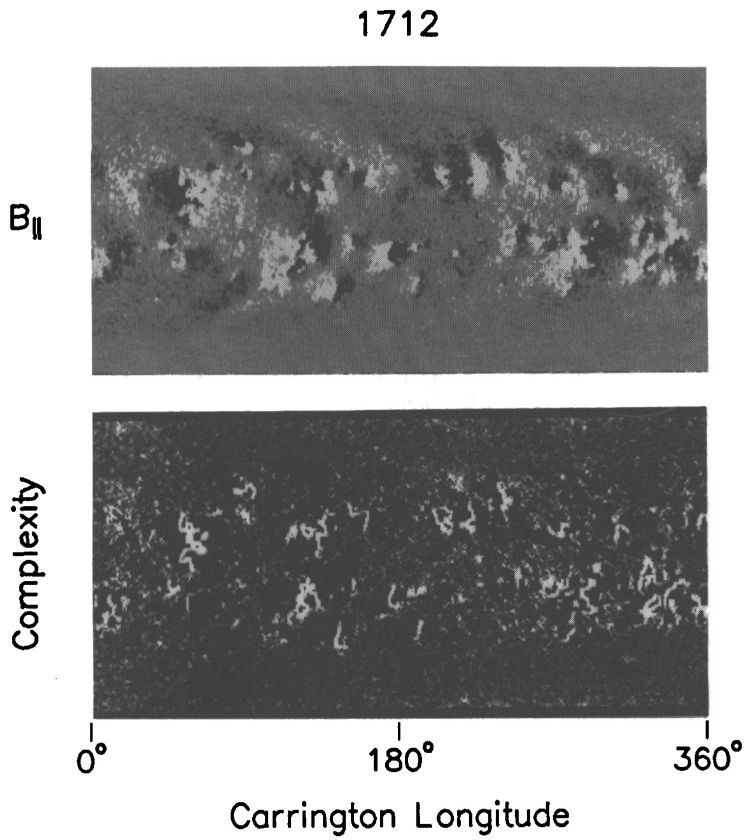

FIGURE 2. Synoptic magnetic map for Carrington Rotation 1712 *(top)* and the corresponding complexity map *(bottom)*.

maps is 1° in longitude and 0.011 in sine latitude; the noise level in the magnetic field data is estimated to be 0.3 Gauss.

2.1. *Technique for isolating active regions*

The first attempt to isolate active regions in the synoptic rotation maps used simply a threshold of 25 Gauss, above which a pixel was considered to be in an active region and below in the 'quiet' Sun (Harvey 1992). In such a procedure, we find that, based on the value of the magnetic field alone, there is an overlap between these two components of magnetic structures. To minimize this effect, a second technique was developed. Active regions were identified in the synoptic rotation magnetic maps by examining the amplitude of the variation of the field within a sub-array of 5 × 5 pixels, i.e. within an area 5° in longitude and 0.055 in sine latitude. Within active regions, it is not expected that over this size area the magnetic flux will be uniform. For each of the 25 pixels in the sub-array, the absolute value of the magnetic field is differenced against the absolute value of the center pixel, and the square of the differences is summed. The square root of the sum

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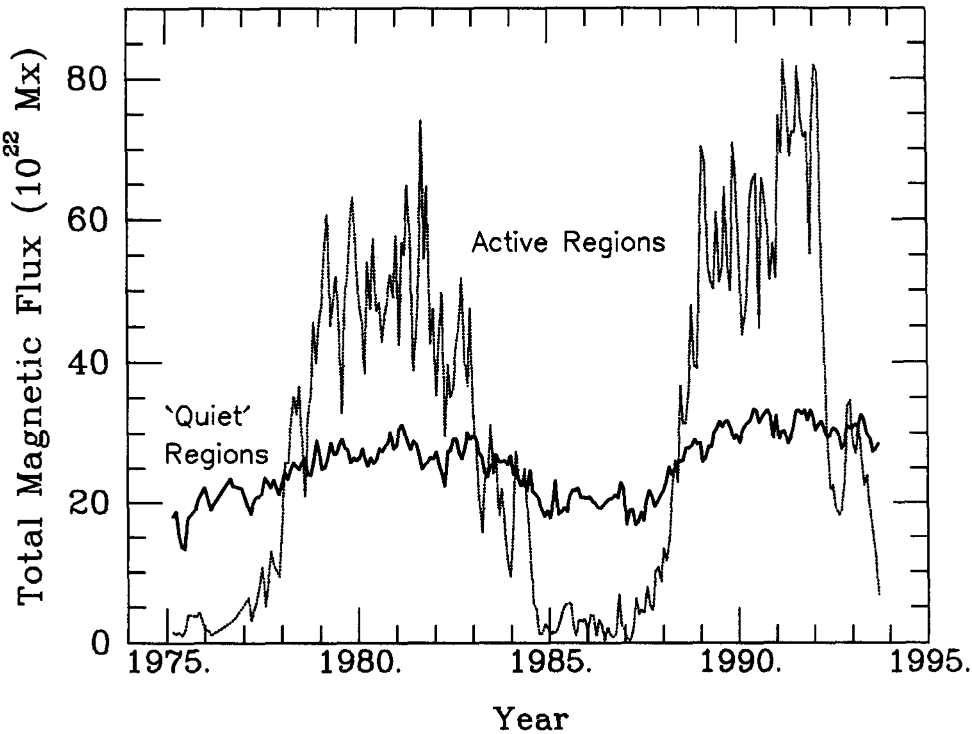

FIGURE 3. Total magnetic flux in active regions *(lighter solid curve)* and in the quiet Sun network *(heavier curve)*, using method described in Section 2.1 to isolate active regions.

over the sub-array, i.e. the root-mean-square-difference, is determined for every pixel in the rotation map. The resulting map of root-mean-square-differences is smoothed to eliminate patchiness and is then thresholded to objectively define the location of active regions. The two separated components of magnetic structures, active regions and the quiet Sun network, are shown in the bottom panels at the left of Figure 1.

Compared to thresholding the data at 25 Gauss, this method to isolate active regions results in less patchy selection of pixels considered to be in an active region, as well as an active region boundary that is expanded slightly outside the isogauss contour of 25 Gauss. There is little magnetic flux in the pixels excluded by thresholding at 25 Gauss, but included by the root-mean-square difference technique, while the area, is larger. In Carrington Rotation 1712, for example, the total magnetic flux in active regions is 3.3% higher using the root-mean-square-difference compared to thresholding at 25 Gauss (71.8×10^{22} Mx to 74.2×10^{22} Mx), while the area within active regions is 60% larger (0.82×10^{22} cm^2 to 1.31×10^{22} cm^2).

2.2. *Technique for defining magnetic complexity*

A measure of the complexity of the magnetic field is determined in a similar way as described above. The sub-array is 3×3 pixels. Within this sub-array, the polarity of a pixel is compared with that of the center pixel. If the pixel is of opposite polarity, the difference between the magnetic field of the pixel and that of the center pixel is squared and summed. This quantity identifies magnetic inversion lines in the rotation maps and

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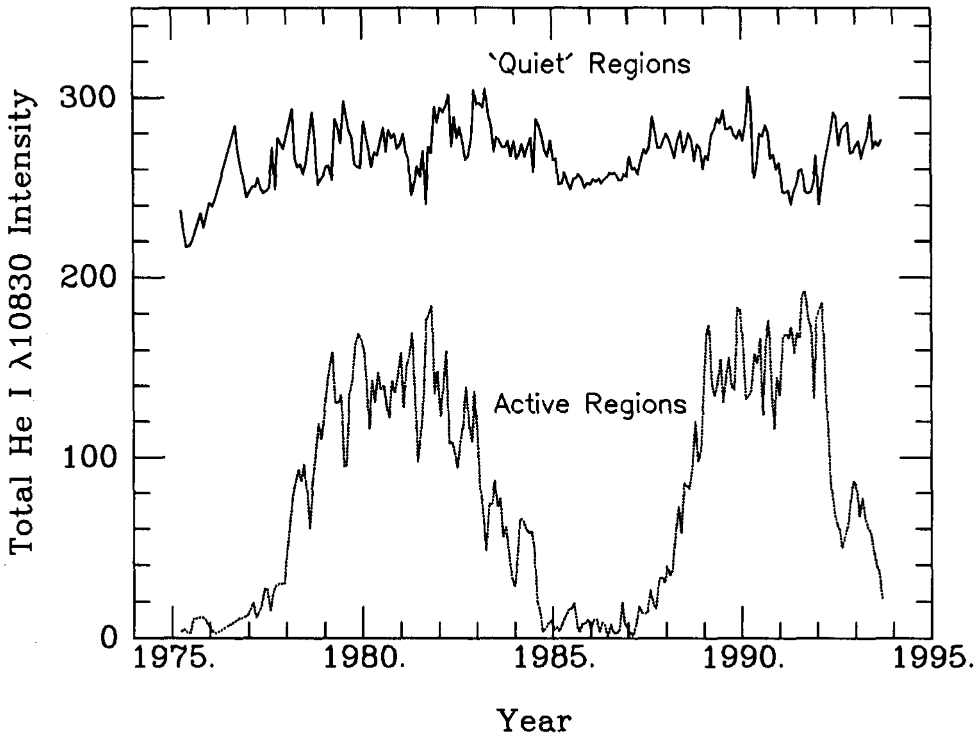

FIGURE 4. He I λ10830 in active regions *(solid line)* and in the quiet Sun network *(dotted line)*, using the method described in Section 2.1 to isolate active regions.

is a measure of the gradients of the field across the inversion line. The 'complexity' map for Carrington Rotation 1712 is shown in Figure 2.

A complexity index defined in this way is sensitive to the noise and the completeness in the daily coverage of magnetograms used to contruct the synoptic maps. If data are missing over extended periods of time, i.e., for more than 4 to 5 days, the information at Carrington Longitudes not observed at their Central Meridian passage is provided by measurements at large heliographic longitudes, where the data are affected by geometrical effects. The poorer coverage (and noisier data) will primarily affect the determination of the complexity index in the quiet sun, leading to generally higher (20 to 50%) values of this index.

3. The active region and the quiet Sun components

3.1. *Total magnetic flux*

Figure 3 shows the variation of the total magnetic flux (the sum of the absolute values of the positive and negative flux) in the two defined components: active regions and the quiet Sun network. These curves are differ little from the total flux determined by thresholding the data at 25 Gauss to separate active regions from the quiet network (Harvey 1992). However, the area included in active region and quiet components does differ significantly using these two methods to define active regions (see section 2.1).

The total magnetic flux in active regions and in the quiet Sun network varies in phase

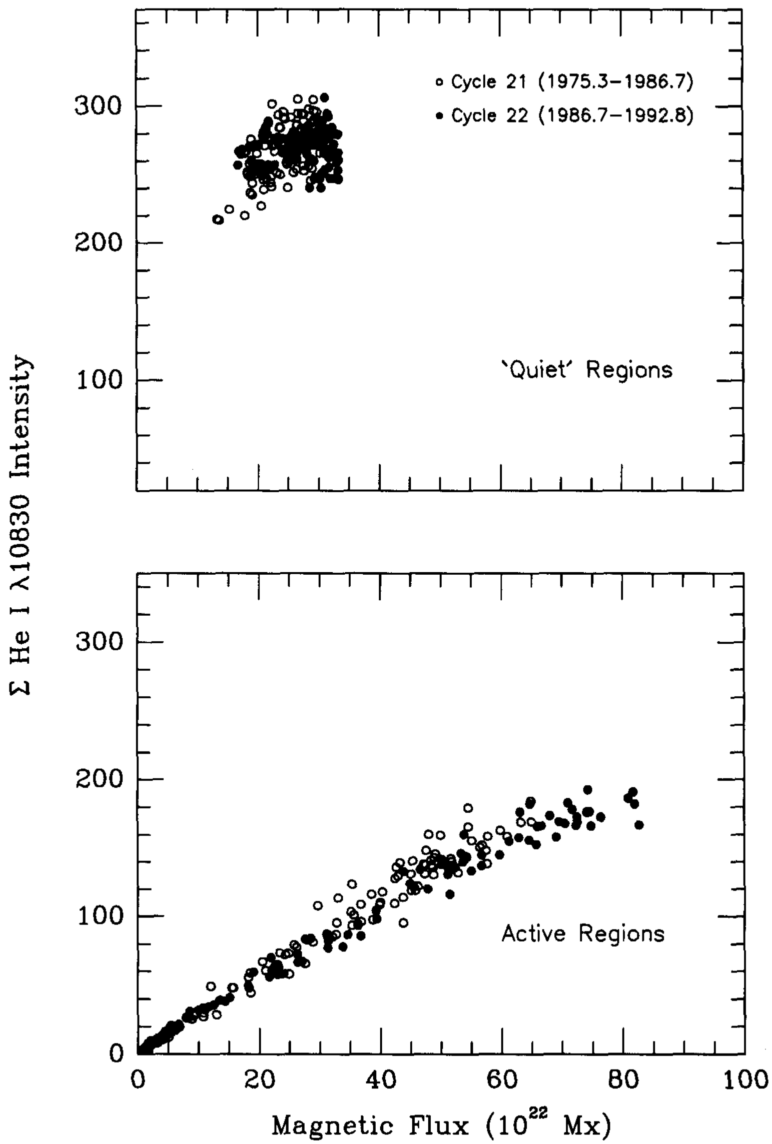

FIGURE 5. Plot of the total He I λ10830 compared to the total magnetic flux in active regions *(bottom)* and in the quiet Sun network *(top)*. Data for cycle 21 is indicated by ∘ and for cycle 22 by •.

during the cycle. However, the total magnetic flux in the quiet Sun network varies from the minimum to maximum phases of a cycle, by no more than a factor of 2, a significantly lower factor than observed for active regions. For approximately half of a solar cycle, the total flux in the quiet Sun network exceeds that in active regions.

3.2. *He I λ10830 absorption*

The active region mask was applied to He I λ10830 rotation maps to determine the corresponding components of He I absorption related to active regions and the quiet Sun

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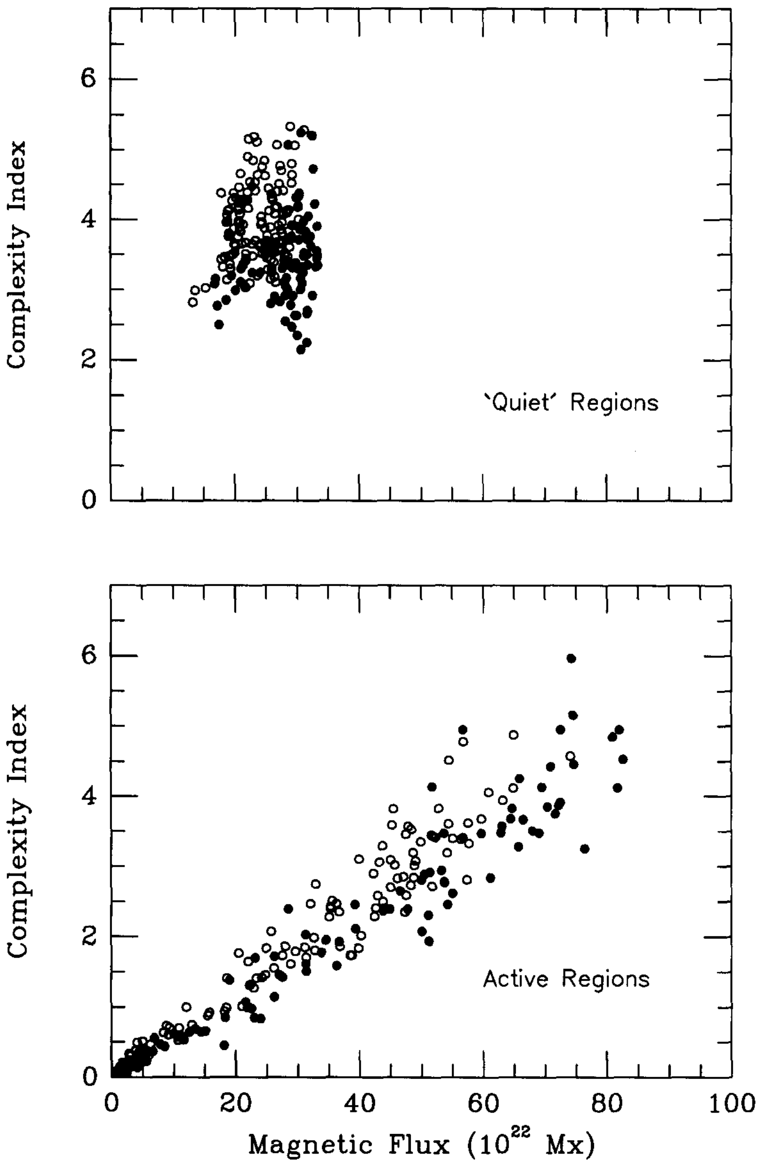

FIGURE 6. Plot of the magnetic complexity index against the total magnetic flux in active regions *(bottom)* and in the quiet Sun network *(top)*. Data for cycle 21 is indicated by ∘ and for cycle 22 by •.

network. The results are shown in the two bottom panels at the right of Figure 1. The variation with time of the total He I λ10830 absorption (summing the He I intensity over the area designated as active regions and as the quiet Sun) is shown in Figure 4.

The total absorption in He I λ10830 observed in the quiet Sun exceeds that observed in active regions over the entire interval of the observations. The quiet Sun component varies little during the cycle. In active regions, on the other hand, the total He I λ10830 shows a strong cycle variation, varying nearly as the total area of active regions. That is, *per unit area* the average level of He I λ10830 in active regions is roughly constant, and is a factor of 2 to 2.5 higher than the He I λ10830 *per unit area* in quiet sun structures.

It should be noted that the He I λ10830 structures in the quiet Sun include network, associated with magnetic network elements, coronal holes, and filaments (see Figure 1). No attempt has yet been made to further separate these individual features in the He I λ10830 data, as is done by Harvey and Livingston (1993).

In Figure 5, the total He I λ10830 absorption is plotted against the total magnetic flux for each rotation, separately for active regions and for the quiet Sun. In the quiet Sun, there appears to be no relation of He I absorption with the magnetic flux. In active regions, however, they are strongly correlated. This is in part a result of their similar cycle variation. The He I λ10830 absorption in active regions increases roughly linearly with increasing total magnetic flux, but differs between cycles 21 and 22. In cycle 22, their relation has a slightly lower slope than is seen in cycle 21. Such variations between cycles also are seen in other spectral irradiance measurements (e.g., Rottman 1988; Donnelly 1991; Harvey 1992).

3.3. *Magnetic field complexity*

The complexity of the magnetic field was investigated in an attempt to understand the differing relation between He I λ10830 and the total magnetic flux between cycles. The premise is, that given the same amount of total magnetic flux, more complex magnetic field structures (activity complexes, active region nests) are associated with higher emission (or absorption in the case of He I λ10830) than a simple bipolar active region. The complexity index defined in Section 2.2 measures, in effect, the linear extent and gradient of the magnetic inversion lines (see Figure 2). Active regions with a complicated magnetic structure have more inversion lines and, therefore, a higher complexity index, than a simple bipolar region.

In Figure 6, the complexity index for each Carrington rotation is compared with the total magnetic flux, separately for active regions and for the quiet Sun network. The complexity of the quiet sun appears to be poorly correlated with the total magnetic flux.

In active regions, for increasing levels of the total magnetic flux (i.e. more active regions on the Sun), there is a corresponding increase in the complexity index of the ensemble of active regions. In cycle 22, however, this increase is less than in cycle 21, suggesting that as a whole, active regions in cycle 22 are less complex than active regions in cycle 21. The sense of the relation between active region magnetic complexity and total magnetic flux between cycles is similar to that seen in the relation of He I λ10830 absorption and magnetic flux. The less complex active regions, overall, in cycle 22, if real, offers one possible explanation of the differing relations of He I λ10830 and other measurements of spectral irradiances between different cycles.

It is important in this interpretation to verify, one objective of future analyses, that there are no long-term instrumental effects that may contribute to the cycle difference in the complexity index either in the quiet sun or active regions.

4. Conclusions

In this analysis, a new objective method to isolate active regions and measure their magnetic complexity is described. Using this method on the synoptic rotation magnetograms, the quite different cycle variation of the total magnetic flux in active regions and the quiet Sun network found by Harvey (1992) is verified. The magnetic flux in the quiet Sun varies in phase with but by a smaller factor (2) than that in active regions (>15). The separation of the active and quiet regions of the Sun was applied to the He I λ10830 synoptic maps. The total He I λ10830 absorption in the quiet Sun exceeds that observed in active regions and varies little with the cycle, while that associated

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with active regions shows a strong cycle variation. The relation between He I λ10830 absorption and the magnetic flux is poor in the quiet Sun, but is strong in active regions. This relation differs between cycles 21 and 22, with the absorption in He I λ10830 being less in cycle 22. Active regions in cycle 22 appear to be as a whole less complex than in cycle 21, offering one explanation for the lower spectral irradiances observed in cycle 22 despite higher levels of total magnetic flux.

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