DEPENDENCE OF UV RADIANCE OF THE QUIET SUN ON THE SOLAR CYCLE

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ABSTRACT

Recent SOHO measurements of UV radiance of the quiet Sun show a dependence of the radiance on the solar cycle. We study the hypothesis that changes in the magnetic network are causing these variations. The quiet-Sun variability is investigated with the two EUV instruments CDS and SUMER and the MDI magnetograph on SOHO. We find that although the magnetic flux of the quiet network increases by a rather low percentage over the rising part of the solar cycle, its variation is well correlated with the radiance change in the He I 584 Å line. The main change occurs in the flux of the strong network elements while the weaker elements do not exhibit a significant change.

Key words: UV radiance, magnetic field.

1. INTRODUCTION

The contribution of the extreme ultraviolet (EUV) spectral range to the total solar irradiance and its variability is, due to its effect on the upper atmosphere, of particular importance for the Sun-Earth connection. That the solar irradiance at UV wavelengths exhibits significant variations over the solar cycle has been known for a considerable time, see e.g., Lean (2001) or Solanki et al. (2001). In general, changes in the magnetic flux at the solar surface and its concentration into dark sunspots and bright faculae or plages are thought to be the drivers of the irradiance variations, although there have also been calls for alternatives. So far, however, this question has been studied in detail only for wavelengths longer than 1600 Å, e.g. by Unruh et al. (1999). The question of the source of EUV variability has become of renewed interest since the discovery that the brightness of EUV lines recorded in selected quiet-Sun regions by SUMER has increased from solar activity minimum to maximum (Schühle et al., 2000). There are different possible explanations for this result. Either the magnetic flux has increased in these "quiet" regions with time, or they have changed in some other fundamental way. Here we test, using MDI magnetograms, whether the former explanation is correct. Motivation for taking this approach is multifold. Firstly, the correspondence of magnetic field strength and radiative intensity is evident from inspection of spectroheliograms and magnetograms, and has been described in several studies, e.g. by Babcock & Babcock (1955), Howard (1959), Leighton (1959), Sheeley (1967), Chapman & Sheeley (1968), Skumanich et al. (1975), Schrijver (1987). Secondly, there is evidence that the density of magnetic elements in the quiet Sun varies over the solar cycle (Muller, 1988), as does the total magnetic flux in the quiet Sun, although only by a small relative amount (Harvey, 1994). The aim of this work is to compare the long-term behaviour of the longitudinal magnetic field measured by MDI with the long-term behaviour of the EUV radiances measured with SUMER and CDS. After a description of the data reduction (Sect. 2), we outline the use of the magnetogram data to follow the Sun's activity cycle, and decompose the images according to their magnetic activity. We then identify co-spatial and co-temporal measurements of the three instruments and investigate trends in the data sets (Sect. 3). A summary of the results and conclusions is given in Sect. 4.

2. DATA DESCRIPTION

2.1. The CDS and SUMER data

The data used in this work, spectral profiles of He I 584 Å, were obtained during Joint Observation Programme (JOP) Intercal_01, during which CDS (Harrison et al., 1995) and SUMER (Wilhelm et al., 1995) pointed simultaneously at the same parts of a quiet region near solar disk centre.

The effective pixel size of CDS is 4″ in the horizontal (cross slit) direction and 1.68″ vertical (along slit), although the actual spatial resolution is lower (Thompson, 1998; Haugan, 1999). The CDS instrument scanned an area of 60″×240″ during this JOP. The CDS data were corrected for burn-in and the flatfield. Prior to November 1996 the monthly SUMER quiet-Sun raster scans registered an area of 60″×300″ with a step size of 0.76″ in east-west direction. After November 1996, the scans were rendered by the drift of the solar surface across the slit due to solar rotation. Thus the area sampled by solar rotation was 3.5″×300″. The SUMER data were corrected for the flatfield, the geometric distortion, and for detector electronics effects such as dead-time and local-

Proc. SOHO 11 Symposium, 'From Solar Min to Max: Half a Solar Cycle with SOHO', Davos, Switzerland, 11-15 March 2002 (ESA SP-508, June 2002)

gain depression. After the instrumental corrections and the radiometric calibration, the solar radiances were determined by integration over the line profiles, which were derived by least-squares fits of single Gaussian functions and a linear background. The background (continuum) was subtracted prior to integration. For more information on the data and the reduction we refer to Pauluhn et al. (1999, 2001).

2.2. The MDI data

The MDI instrument (Scherrer et al., 1995) provides measurements of the photospheric longitudinal magnetic field. For our studies we selected the full disk 5-minute integrated magnetograms that have a spatial binning of 2″ per pixel. These images are taken regularly every 96 minutes, 15 per day, and have a noise level of $\sigma_{\text{ns}} = 9$ G (A. Kosovichev, personal communication, 2001). To match the available CDS and SUMER data, the magnetograms closest in time to the EUV instruments' data were selected and the co-spatial areas were identified after compensating for solar rotation. From the 1024 px × 1024 px full disk MDI image we extracted a box of 200″× 400″ (100 px × 200 px) centered around the CDS image centre coordinates. A first approximation of the absolute magnetic flux density was computed as the absolute values of the MDI data in the box. Via two-dimensional cross-correlation the areas co-spatial to the CDS and SUMER images were determined where possible. For SUMER, raster scan images were available on a regular basis only for measurements made prior to November 1996. Afterwards such scans were made only at single dates, such as 6 August 1999 and 2 November 1999.

3. TIME SERIES OF FULL DISK AND QUIET AREAS

In the following we compare the average absolute flux densities in the full disk images with those of the smaller quiet areas comparable to the SUMER and CDS images. In the full Sun images, the mean value of the magnetic flux density increases by 30 % over the four years (mid 1996 to mid 2000), while in the smaller boxes in quiet areas the increase is roughly 10 %. Similarly the variability (standard deviation of the magnetic flux density) in the full Sun magnetograms rises by a factor of nearly four, and just doubles in the quiet areas (Pauluhn & Solanki, 2002). Various authors, see e.g., Harvey & White (1999), have pointed out that for a reasonable decomposition of the solar magnetic field at least four different activity ranges have to be distinguished. Hence, we distinguish between different levels of magnetic flux density as given in Tab. 1 and calculate their fraction on the full disk and the quiet areas, respectively. The temporal evolution of the fractions covered by the zones of different magnetic activity over the four years of our sample is shown in Figs. 1 and 2. The fractions of the area covered during low solar activity (referred to as "min" in Tab. 1) have been calculated from the values in 1996, and those near the maximum of solar activity (referred to as "max") have been calculated from the values in 2000. Other authors, see e.g., Harvey & White (1999) and references therein, introduced finer scales and elaborate pattern recognition techniques to distinguish between the various types of activity, but here we use simple thresholds for the partition. We justify this by the fact that to first order we expect that the radiative flux in chromospheric and transition-region lines depends on the spatially averaged strength of the magnetic field and only peripherally on the type of structure to which the field belongs (with the exception of sunspots, which however are only found in active regions and do not affect our analysis).

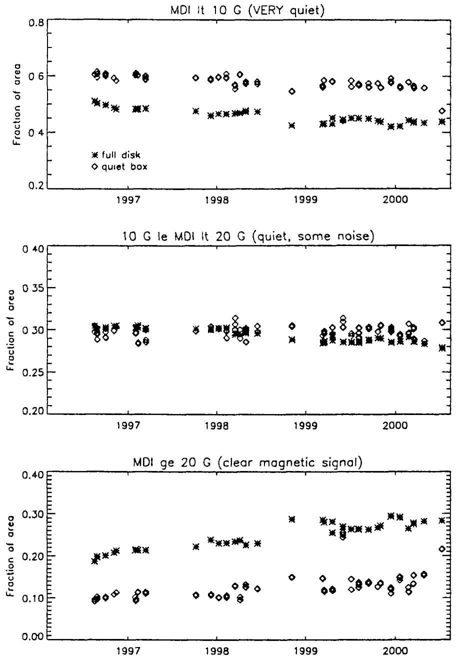

Figure 1. Time series of the fractions of different activity ranges in the MDI images for the full disk and a quiet area of 120″× 400″.

We select five different levels: one very quiet, below 10 G, the following level of 10 G – 20 G, also being relatively quiet, 20 G – 40 G containing quiet network areas, 40 G – 60 G containing more enhanced network parts, and everything above 60 G we regard as enhanced network. These values should be compared with the noise level σ_{ns} of roughly 9 G. Hence the first and second bins contain points with magnetogram signals (abbreviated by "MDI" in Tab. 1) below 1.1 σ_{ns} and 2.2 σ_{ns}, respectively. Consequently, the first bin is completely, the second still heavily dominated by noise. The third bin, containing signals between 2.2 and 4.4 σ_{ns} is still somewhat affected by noise, while the final two bins exhibit practically only a real signal. As shown by, e.g., Ortiz et al. (2002), the noise level in MDI full-disk magnetograms is not constant over the field of view, being larger near parts of the solar limb. This may partly explain the difference in the fraction of pixels in the 0 G – 10 G bin between the full disk and the quiet area at activity minimum. This difference also indicates that the regions observed by CDS and SUMER were indeed very quiet. Over the entire so-

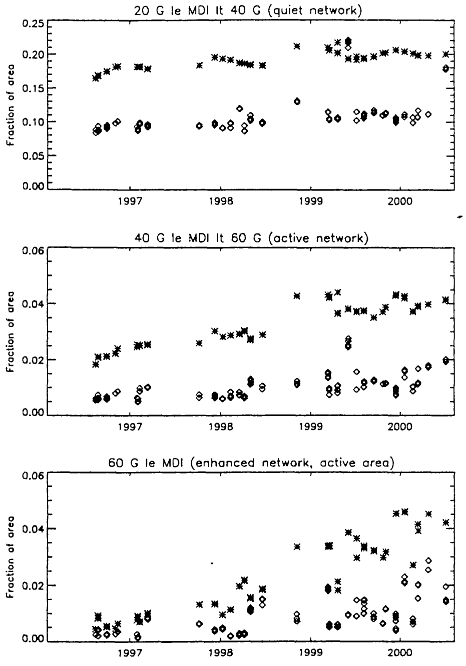

Figure 2. The same as in Fig. 1, for areas of higher magnetic activity.

lar cycle the quiet areas are strongly dominating. Skumanich et al. (1975) identified 39 % as network area covering the *quiet* Sun by separating the distribution of the magnetic field values into a Gaussian core part and a tail. If in our quiet areas we consider everything above the "noise limit" or "very" quiet Sun as network, the partition of roughly 40 % network, and 60 % non-network (i.e. cells) is confirmed and also rather stable over the solar cycle. However, the very quiet area is reduced by about 3 % from minimum to maximum phase. For *full disk* images, the fraction of the very quiet areas decreases from 50 % at solar minimum to 40 % at solar maximum. These changes are compatible with the increase of magnetic activity with time, so that the current data set is in agreement with the conclusion of Ortiz et al. (2002) that the noise in MDI full-disk magnetograms is practically time-independent. Both, Tab. 1 and Figs. 1 and 2, show that the relative rise in flux between activity minimum and maximum increases rapidly with flux density, with both the full-disk and quiet Sun data exhibiting a very similar behaviour.

Next we turn to the comparison between the data sets from the three instruments. For CDS the exact cospatial regions could be determined for all data sets, while for SUMER this was only possible in a minority of cases. For the remaining SUMER data sets (those without spatial scanning) only the averages over the entire images were compared. In Fig. 3 the time series of the image averages of these data sets are shown. The MDI data were not restricted to exceed a certain noise cutoff, so that the noise is still included in this data set. The correlation of the cospatial CDS and MDI time series amounts to 0.70. The correlation of the SUMER and MDI time series amounts to 0.67 for the MDI images of $60'' \times 300''$ (SUMER mainly $3.5'' \times 300''$, or, where available, $60'' \times 300''$) both centered around the CDS/SUMER image center.

Table 1. Percentage of area covered by the different magnetic field ranges. The percentage at "min" has been calculated from the data in 1996, at "max" from the data in 2000.

	full disk (∗)		quiet box (◇)	
	min	max	min	max
MDI < 10 G	50	43	60	57
10 G ≤ MDI < 20 G	30	29	30	30
20 G ≤ MDI < 40 G	17	20	9.25	10.5
40 G ≤ MDI < 60 G	2.25	4	0.5	1.25
60 G ≤ MDI	0.75	4	0.25	1.25
20 G ≤ MDI	20	28	10	13

Figure 3 has two purposes. Firstly, it shows that the SUMER and CDS radiances, averaged over the complete scanned area run approximately in parallel. Differences between the two curves are partly due to the different times at which the data were recorded (CDS measurements without SUMER counterparts and vice versa) and the fact that most SUMER and CDS data sets also do not sample the same spatial area. A detailed comparison between the data from the two EUV instruments as well as a discussion of the uncertainties involved has been published by Pauluhn et al. (2001, 2002). Secondly, Fig. 3 allows the evolution of the EUV radiance to be compared with that of the magnetic flux. Here too a good correspondence is visible. Already such a qualitative comparison suggests that the magnetic flux variations are responsible for the EUV flux variations. To obtain more quantitative estimates, we performed linear fits to the time series of the CDS data, the MDI data measured simultaneously with CDS, the SUMER data, and the MDI data measured simultaneously with SUMER. The trends are strongly influenced by the selection of data points, e.g., by the choice of initial and end points for the fits, or by the distribution of the measurements, associating more weight to a time period with relatively many measurements. The uncertainties on the percentage of increase have been estimated from the increases as produced by the two extreme curves from the fit uncertainties in the two coefficients (constant a_0 and slope a_1), i.e. from the curves $(a_0 \pm \sigma_0) + t \cdot (a_1 \pm \sigma_1)$. Data points obviously contaminated with parts of active regions (like e.g. in June 1999 and March 2000) have been omitted from the fits. For the CDS time series we find an increase from May 1996 to May 2000 of (17 ± 10) %. The MDI data at the same dates and locations give an increase of (11 ± 5) %. For the co-temporal time series of SUMER and MDI, the relative increase amounts to (22 ± 25) % and (20 ± 15) %, respectively. The uncertainty in these values is large and is dependent on the sampling. The amount of SUMER measurements, for example, is smaller by nearly a factor of four, leading to larger uncertainties for the corresponding linear fit parameters.

However, in all fit scenarios a positive trend can be found. For the CDS and MDI data, the most pessimistic restrictions were those of omitting the first dates until March 1997 and those later than March 2000, giving small in-

creases of 8 % (CDS) and 6 % (MDI) in four years.
Does the generally smaller relative increase in unsigned magnetic flux than in radiance mean that the magnetic flux is responsible for only a part of the increase in quiet Sun brightness towards solar activity maximum? This problem is aggravated by the fact that the radiance actually increases sublinearly (approximately as the square root, see Harvey & White (1999); Pauluhn & Solanki (2002)) with magnetogram signal, when considered pixel by pixel (Frazier, 1971; Schrijver et al., 1989). In the above estimates the noise was included. The S/N ratio of the He I line observations is considerably larger than for the magnetograms. In order to remove any possibly noise-induced bias we also exclusively consider the signals above 1.1 $\sigma_{\rm ns}$ and 2.2 $\sigma_{\rm ns}$ in each data set. Omitting the MDI signals below 1.1 $\sigma_{\rm ns}$ increased the correlation between the average radiances and average flux densities by roughly 5 % with the CDS data and 10 % with SUMER, whereas considering only signals larger than 2.2 $\sigma_{\rm ns}$ did not lead to better correspondence between the time-series. The increase in the MDI data in the CDS sampling was reduced to approximately 8 %, and to 13 % in the SUMER sampling for signals greater than 1.1 $\sigma_{\rm ns}$ as well as 2.2 $\sigma_{\rm ns}$. In summary, a positive trend can be detected in all data sets, a realistic range of it would be a 10 to 20 % increase over four years. These fits have been made using approximately monthly measurements, with different temporal sampling during different periods, and as shown, the amount of the increase is not easily determined but strongly dependent on the chosen fit period. Nevertheless, this seems to confirm the findings of Schühle et al. (2000), who noted a positive trend in SUMER quiet Sun measurements. Our finding of an increase in the averaged magnetic flux of these areas supports the idea of a non-negligible contribution of the quiet Sun to the variability during the solar cycle.

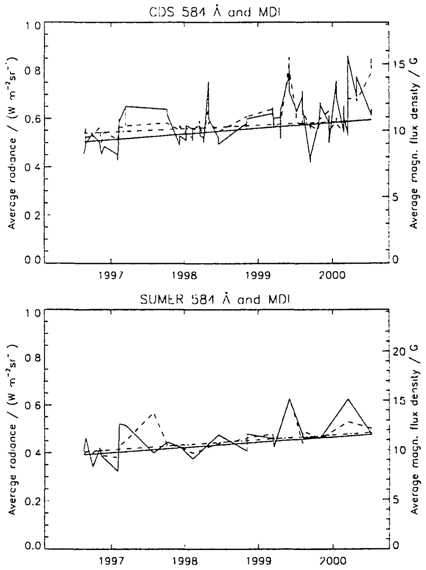

Figure 3. Time series of the average values in the SUMER and MDI images. The solid lines give the radiance data, and their linear fits, the dashed and dot-dashed lines give the MDI data and their corresponding fits. All shown fits give an increase of 11 % to 22 % within the four years from June 1996 to June 2000.

4. SUMMARY AND CONCLUSIONS

Four years of nearly monthly measurements of magnetic field and chromospheric EUV radiance of quiet regions near solar disk centre have been studied and compared, using data from SOHO's MDI magnetograph and the two EUV spectrometers CDS and SUMER. The time series begin in 1996 during the activity minimum between solar cycles 22 and 23 and accompany the rise of cycle 23 until mid 2000.
While the magnetic flux density measured over the full solar disk increases by 30 % during the period, the increase in the quiet areas amounts to only 10 %. This increase is due to a rise in the network area where the magnetic signal exceeds 20 G. The area of the network measured over the full disk amounts to 20 % near solar minimum conditions and it rises to 28 % near maximum conditions. For the studied quiet areas this network area covered 10 % of its total area during less active conditions and its fraction increased to 13 % near maximum solar activity, an increase by a factor of 1.3.
Similarly, a small increase is recognized in the time series of radiances in He I 584 Å measured by CDS and SUMER. Thus, independent measurements of the two EUV instruments and the MDI magnetograph on SOHO seem to indicate that the so-called quiet Sun has a significant influence on solar variability.

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