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LETTER

Letter to the Editor

Radiance variations of the quiet Sun at far-ultraviolet wavelengths

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Abstract. We have measured the radiance of quiet-Sun areas at the centre of the solar disk using the vacuum-ultraviolet telescope-spectrograph SUMER (Solar Ultraviolet Measurements of Emitted Radiation) on the Solar and Heliospheric Observatory (SOHO). The radiances of selected emission lines have been measured from March 1996 to the present. The lines that have been observed regularly since the beginning of the SOHO mission are He I 584 Å, Mg X 609 Å and 624 Å, Ne VIII 770 Å, N V 1238 Å, and the H I Lyman continuum at 880 Å. We investigate the variability of these emission lines during the solar minimum and the ascending phase of the present solar activity cycle. The transition region and coronal lines show an increasing trend of up to 100% since the sunspot minimum. The results are important for models of solar VUV variability on the basis of radiance contrast ratios of solar disk regions. Our spatially resolved images allow a separation of the network and cell areas of the quiet-Sun. Both regimes show similar variations.

Key words: Sun: UV radiation – Sun: radiometry

1. Introduction

The solar irradiance in the ultraviolet and its variability is of fundamental importance due to its effect on the upper atmosphere of the Earth. In several spectral lines in the UV and EUV, the irradiance has been measured by the SUMER spectrograph (Solar Measurements of Emitted Radiation) on the Solar and Heliospheric Observatory (SOHO) during 1996 and 1997 (Wilhelm et al. 1998). From the spatially resolved images of the Sun, the contributions of active and coronal hole regions could be obtained, that contribute to the short term variation of the irradiance of spectral lines due to solar rotation. These results provide important input parameters for models of the solar irradiance spectrum (Fontenla et al. 1999) and the VUV irradiance variability based on the contrast ratio of different regions on the solar disk. It was also possible to measure the detailed centre-to-limb variations in these emission lines.

The long-term variability on the other hand, which goes along with the solar activity cycle, is known to be very strong (Hall et al. 1969), but has not been measured for many spectral lines (Tobiska et al. 1998, Woods et al. 1998) and is not understood in detail (Lean 1991). In particular, it is unclear whether the variability of the irradiance of the Sun can be modelled by active region and plage area contributions or is also due to a global change of the quiet-Sun radiance. The latter can be a global brightening of the emission or may be caused by changes of fine scale structures in the chromospheric and transition region network. Even a change in the statistics of transient brightenings may be possible.

The SUMER spectrograph on SOHO has been calibrated in the laboratory before the launch of SOHO. The careful tracking of the instrument responsivity during the mission has been accomplished by repeated observations of quiet-Sun areas on a regular basis. These measurements have shown that the responsivity had not degraded during two and a half years of the mission. Contrary, an increasing trend of the radiance of some lines was found. The measurements can thus be used to derive long term variations of the radiance of the observed spectral lines. The spatially resolved images give us a first clue about the variability of different spectral lines from the chromosphere, transition region and the lower corona and its relation to the network structure.

2. Instrument and calibration

SUMER is a stigmatic normal-incidence telescope-spectrograph operating in the wavelength range from 465 Å to 1610 Å using two orders of diffraction in superposition. In their common wavelength range between 465 Å and 1480 Å, one of two identical detectors (detector A and B) can be used for observations. Each photocathode of the detectors has two areas (bare microchannel plate and potassium bromide coating) with different spectral responses which can be used to separate the first and second order contributions. The telescope mirror can be stepped in multiples of single steps of $0.38''$ to move the solar image across the spectrometer entrance slit ($1''$ corresponds

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to ≈715 km on the Sun). The slit with angular dimensions of $1'' \times 300''$ is imaged by the spectrograph on the detectors with a resolution element of about $1''$ per pixel in spatial direction and 44 mÅ per pixel in the spectral regime.

The instrument has been calibrated with both detectors before flight using a transfer standard source which itself had been calibrated against the primary radiometric source standard BESSY I (Hollandt et al. 1996). This laboratory calibration established the responsivity of the instrument at a set of wavelengths provided by the transfer source. By the fact that none of the observed lines presented in this communication showed any decline of intensity, it could be verified that the instrument responsivity was stable during the mission time (Schühle et al. 1998) until the SOHO accident when the nominal spacecraft attitude was lost for three months. Particularly, the use and comparison of the two detectors, when only one detector had been used during half a year, indicated that there was no systematic effect of any one detector. After the recovery of SOHO, a change of responsivity of SUMER was found. From continued measurements, the trends before and after the accident have been compared, and a loss factor could be derived for those wavelengths measured.

The relative uncertainty levels of the radiometric calibration were 15% (1σ) for the A detector (Wilhelm et al. 1997) and 20% (1σ) for the B detector (Schühle et al. 1999) in the range from 540 Å to 1250 Å and 30% for longer wavelengths.

3. Observations and data calibration

For the tracking of the calibration of the SUMER instrument during the SOHO mission, a set of five emission lines had been selected that have repeatedly been observed in quiet-Sun areas near the disk centre. Since March 1996, these observations have been performed roughly once every month and are continued. The lines measured during the observing sequence are He I 584 Å, Mg X 609 Å and 624 Å, Ne VIII 770 Å, N V 1238 Å. The He I and the Mg X lines are in second order, while the N V line is in first order. The Ne VIII line is observed in second order with the A detector whereas it is seen in first order with the B detector.

To exclude any contributions from active or bright regions, an area close to disk centre was always selected that was devoid any solar activity by referring to the He II 304 Å images of the Extreme-Ultraviolet Imaging Telescope (EIT) of SOHO. An area of $60'' \times 300''$ was registered by a raster scan of the telescope with a step size of $0.76''$ in east-west direction. After September 1996 the raster scan mode was given up, and instead the slit was kept at a fixed position, letting only the solar image drift across the slit by the solar rotation. Each line was registered for 21.3 minutes, taking 80 exposures of 16 sec. Each raster was registered once during one run, while the Ne VIII line was registered four times. The area sampled by solar rotation was $3.5'' \times 300''$. So the area sampled was much smaller, and thus the sample of the chromospheric network structure was only marginally representative, when the raster scan was not invoked. But nevertheless, the size of this area warranted that always a part of network and cells was sampled. Recently, in August 1999, the raster scan mode was resumed.

An additional set of measurements was obtained by an observing sequence of the hydrogen Lyman continuum, performed independently but with similar regularity. In these observations a spectral window of 40 Å of the H I Lyman continuum at 880 Å was sampled for three hours at a quiet-Sun area, corresponding to a raster area of about $30'' \times 300''$.

4. Results and discussion

For each measurement we obtain the average radiance in the observed area. From 5 March 1996 to 8 August 1999 we have made 34 observations. A summary of all the results is presented in Fig. 1. It shows the evolution of the absolute radiance of each line in the entire time period starting well before the minimum of the sunspot activity between solar cycles 22 and 23. On 26 August 1996 a comparison between detector A and B has been made, and from thereon, for most of the time the B detector has been used. After the recovery from the SOHO accident, that occurred between June and September 1998, both detectors have been used alternately. Thus we can exclude any variation due to changes of response of one detector. A loss of responsivity associated with the SOHO accident phase has been determined in the analysis of these data. By minimizing the difference between a linear least squares fit to the data before and after the accident, for each line individually a change of responsivity between 25% and 45% has been compensated.

All lines show an increase of radiance during the observed time period. The He I 584 Å line shows the smallest variation, perhaps because this chromospheric emission originates at a lower level in the solar atmosphere, and, contrary to the other lines, it is optically thick. For the other lines the increase of radiance amounts to more than 100% and probably will continue as we reach the next solar maximum. The H I Lyman continuum at 880 Å shows an increase of nearly 75%.

We estimate overall uncertainties of the radiance values to be within 15% (1σ) for all lines observed. The variations of data points however are much larger due to variation of the radiance inside the sampled area. This has been proven by a comparison with data measured in coregistration by the CDS (Coronal Diagnostics Spectrometer) instrument on SOHO. These data have been evaluated for the first 150 days, and they agree on the absolute scale within the uncertainty margins given by both instruments. The data show in particular that the variations are in phase for both instruments (Pauluhn et al. 1999). Thus the scatter of data is not instrumental and would perhaps be reduced if a larger area were sampled. Despite the scatter on the short time scale, the long-term trend is clearly discernible.

Next we investigate the spatially resolved images. We try to separate the network areas from the cell interior locations (areas of lower radiance) by integrating for each line those locations separately where the intensity is 25% above and below the average. In Fig. 2 we have plotted the radiance variations of the lines Mg X 609 Å and 624 Å, N V 1238 Å, and He I 584 Å on a normalised scale. We plotted the network locations, i. e. the

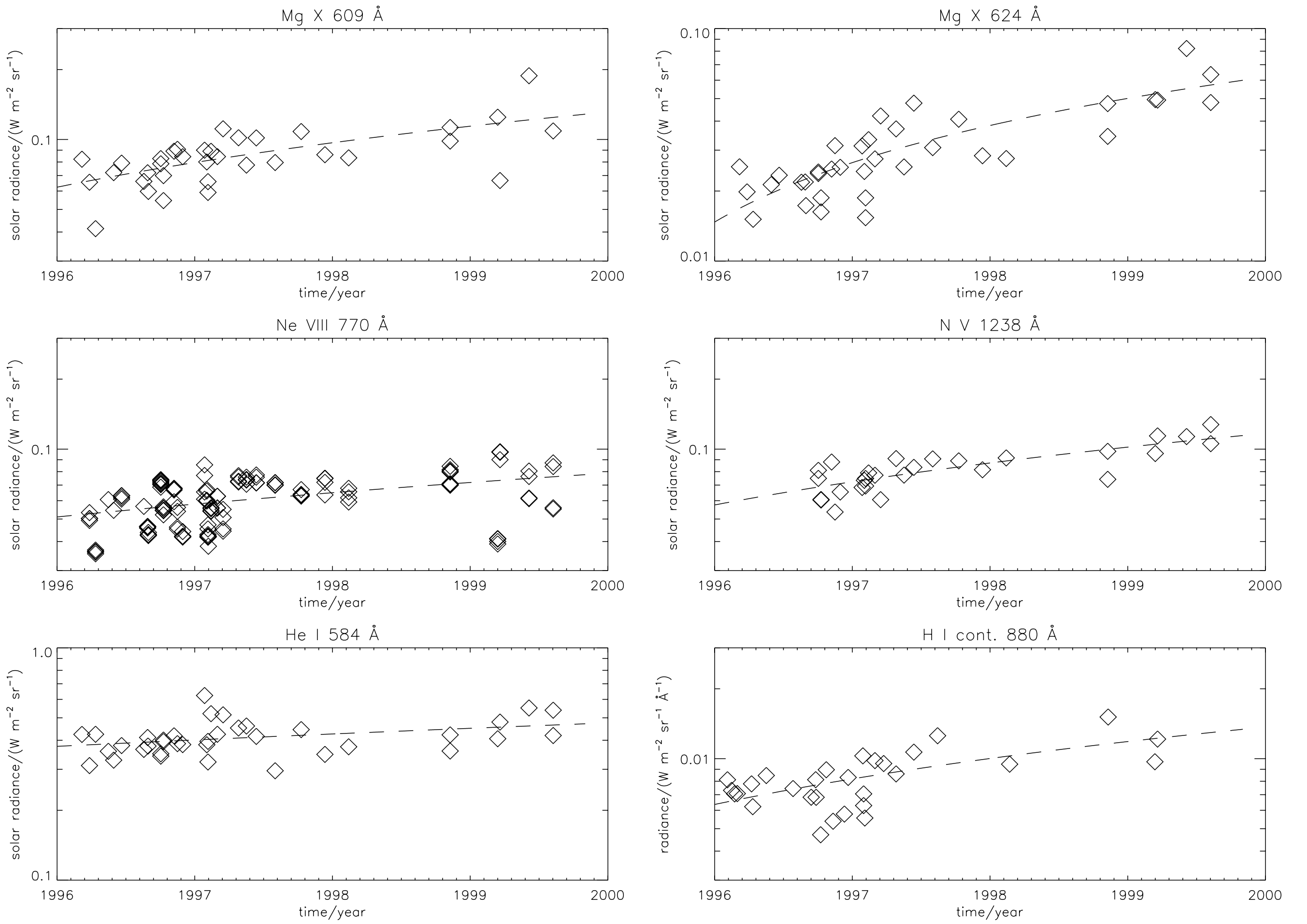

Fig. 1. Radiances of the lines of Mg X 609 Å and 624 Å, Ne VIII 770 Å, N V 1238 Å, He I 584 Å, and the H I Lyman continuum at 880 Å measured at quiet-Sun areas between 5 March 1996 and 8 August 1999. A linear fit was applied to each data set. For better comparability, the radiances in each plot are scaled over one decade.

highest 25% of the intensities, and the areas of less brightness, i. e. the lower 25% intensities. A linear fit was applied to the data to represent the variations. In each of these lines we see the increase of the radiance in both, the network and cell regimes. For the N V line only data after solar minimum are available. But for this line, which is formed at regions of lower temperature with more detailed network structure than the Mg X lines, we see that there is no difference in the variability of the network and the cell interior areas.

We conclude that the radiances of the lines of N V, Mg X, and Ne VIII, which originate in the transition region and the lower corona, show an increase in quiet-Sun areas that seems to be associated with the solar activity cycle. This result implies that the variation of the irradiance from the full Sun cannot simply be modelled by the number of active regions and plage areas visible on the solar disk and their variation throughout the solar cycle. Instead, there is an additional contribution to the variability from the quiet solar network. We find that the increase of radiances from solar minimum to August 1999 amounts to between 45% and 100%. The separation into bright and dark areas reveals that both, the network regions and the darker regions show the same relative amount of increase. Thus it seems that the variability is a global brightening of the emission of these lines in quiet-Sun regions, or the variation is not resolved by the SUMER instrument.

We stress that the scatter of data points is much higher than photon counting statistics and is entirely of solar origin, as a result of the limited size of the sampled area. Also, as we approach the maximum of the solar activity cycle, it becomes more difficult to select regions on the solar disk that are not influenced by active regions nearby, and the term "quiet Sun" may become questionable. We must notice also that the maintenance of the radiometric calibration over such a long period is a difficult task, and any error in this procedure will influence these results. It is therefore extremely valuable to have such observations from several independent instruments on SOHO. A joint evaluation of the data from SUMER, UVCS, and CDS instruments is underway.

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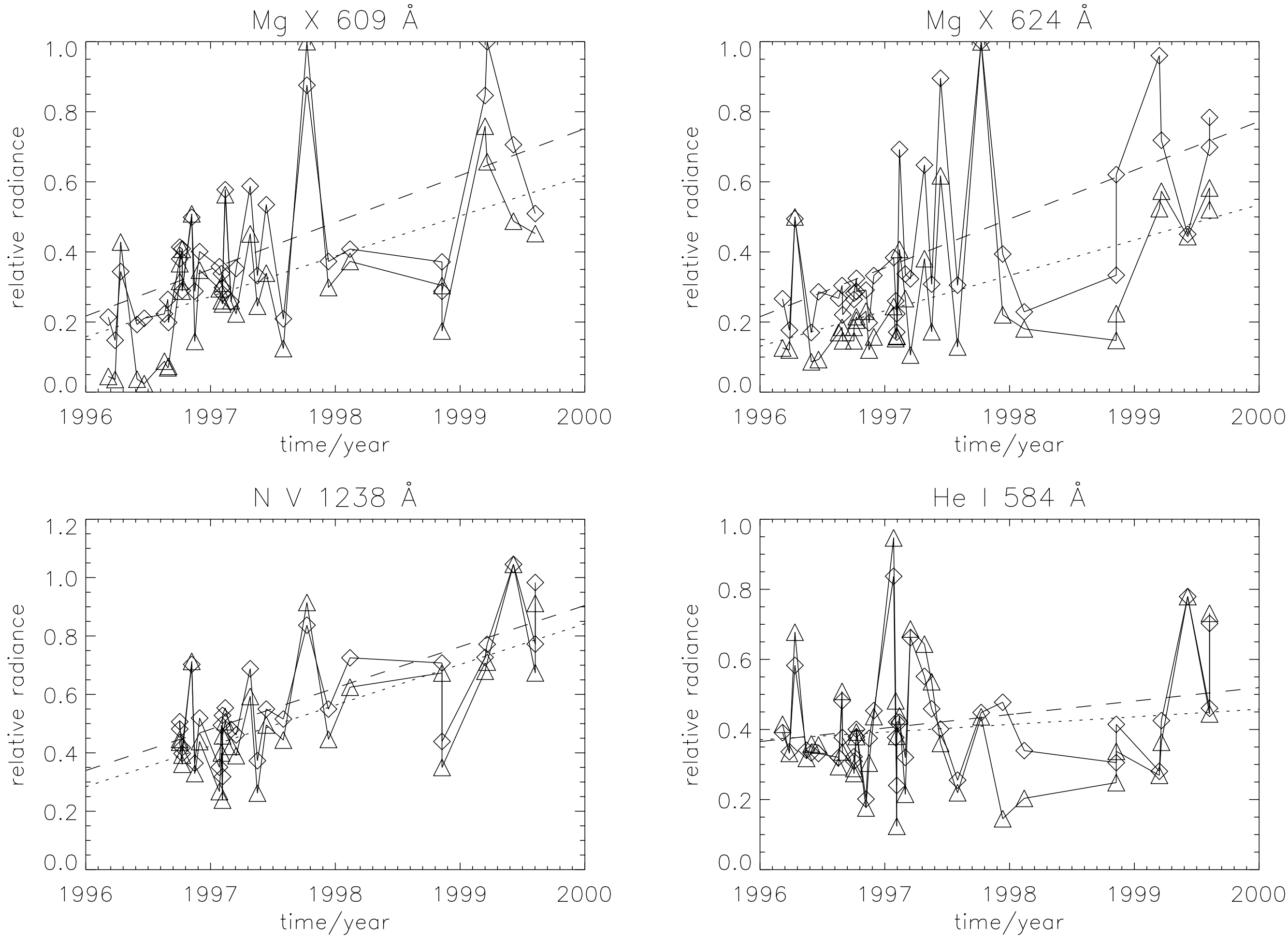

Fig. 2. Relative variation of the radiances of the network (highest 25% of intensities) and cell regions (lowest 25% of intensities) of the lines Mg X 609 Å and 624 Å, N V 1238 Å, and He I 584 Å. Diamonds and dashed lines represent the network regions, triangles and dotted lines represent the cell regions. The dashed and dotted lines are each a linear fit to the data.

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