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The EUV spectral irradiance from 1996 to 2003 as obtained from SOHO

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Abstract. We present EUV (150-800 Å) radiance measurements obtained with the SOHO/Coronal Diagnostic Spectrometer (CDS) during the period from 1996 to 2003. We complement the CDS measurements with simultaneous SOHO/EIT EUV images. We use the EIT center-to-limb variations to obtain an estimate of the EUV spectral irradiance of the 'quiet Sun' during 1996-2003. We discuss the evolution of the characteristics of the solar corona from minimum to maximum, and show how it becomes progressively hotter.

Key words. Solar corona – EUV spectral irradiance

1. Introduction

Solar extreme ultraviolet (EUV) and soft X-rays (X) irradiances between 10 and 1200 Å are the primary source for the photoionisation in the ionosphere. A large variability in the EUV irradiance is known to be present, however details are still not known. Before SOHO, most of the XUV measurements of the spectral irradiance were made using rocket flights in the 60's and 70's.

SOHO instruments do not measure the XUV spectral irradiance, however they measure spectral radiances (CDS, SUMER), total irradiances in some spectral bands (CELIAS/SEM), or simply provide broad-band EUV imaging (EIT). Since its launch in December 1995, SOHO has thus provided a large dataset – from solar minimum (1996) up to now, through the maximum (2001-2002) – containing important information on the solar EUV irradiance. Here we will focus on CDS and EIT data.

The CDS instrument is composed of a Normal Incidence (NIS) and a Grazing Incidence (GIS) Spectrometer, covering, with a few minor gaps, the 150-800 Å spectral range. While CDS has been providing spatially resolved spectral data of the Sun since 1996, EIT has been providing broad-band images of the Sun centred at 171, 195, 284 and 304 Å. We present here preliminary results of a long-term plan which aims at obtaining the EUV spectral irradiance and at studying its characteristics from minimum to maximum. The plan is to first provide EUV (150-800 Å) radiance measurements of various solar features (coronal holes, 'quiet Sun', active regions) obtained with SOHO/CDS. The few data gaps will be filled using CHIANTI atomic data (Young et al. 2003) and emission measure techniques (Andretta et al. 2003). Then, to use EIT images and the FULL SUN NIS spectral radiance

Send offprint requests to: G. Del Zanna measurements (Brekke et al. 2000) to study the center-to-limb behaviour as a function of the temperature of the emission lines, and the contribution (on-disc, off-limb) of the various solar features to the EUV spectral irradiance over the solar cycle. We will then be able to study in detail the physical characteristics of the solar corona from minimum to maximum.

An important by-product of this work is a check on the consistency of the cross-calibration between the different SOHO instruments. After two workshops held at ISSI (cf. Del Zanna (2002), and the book 'The radiometric calibration of SOHO'), the various teams have converged to a consistent relative radiometric calibration between the various instruments within 30-50%, but only for the first years of the mission, and at few selected wavelengths. Large uncertainties in the long-term ageing of each of the SOHO instruments are still present and a lot more work is still needed.

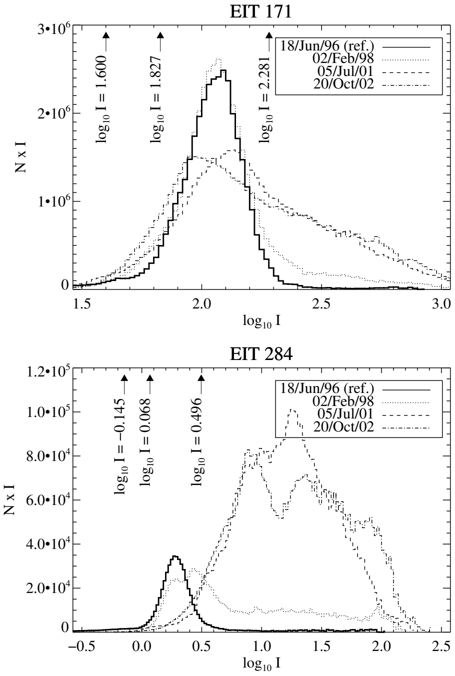

Fig. 1. SOHO/EIT histograms at four selected times in the 171 and 284 Å bands, obtained from images corrected for limb-brightening, and excluding off-limb pixels.

2. Analysis and results

We have used SOHO/EIT images to study the histograms of the intensity distribution along the cycle (see, e.g. Fig. 1). The SOHO/EIT histograms of 1996 (solar minimum) were used to define intensity levels for coronal holes, quiet Sun and active regions (Fig. 1). To enhance the contrast between different regions, in each EIT image, from on-disk pixels we have removed a limb-brightening factor obtained by assuming an hydrostatic, isothermal and spherical atmosphere (Andretta et al. 2003). Also, to facilitate comparisons of images at different epochs, we have used the same scaling factor for displaying all four images.

We also obtained the distribution of the various solar regions from the EIT images. We have found how the different regions on the Sun contribute differently over the cycle in terms of fractional area of the disk (see Fig. 3) and average count rates (see Fig. 4). The EIT 304 Å band, dominated by He II ($T < 0.1$ MK), and the 171 Å band, dominated by Fe IX, Fe X emission ($T = 1$ MK), show an increase in the areas covered by active regions (AR) of up to 20%. The averaged count rates of the 'quiet Sun' do not change appreciably. On the other hand, the EIT 195 Å band, dominated by Fe XI and Fe XII ($T = 1.3$ MK), and the 284 Å band, dominated by cooler and hotter (Fe XV, $T = 2$ MK) lines, show a steadily decrease of 'quiet Sun' regions, up to a point where no more such regions are present anymore (as also shown in the histograms).

For the CDS data, we have analysed the synoptic GIS observations of the quiet Sun during 1996-2003. These observations consist of 30" × 30" raster scans, performed routinely with the exception of the period of the temporary loss of contact with SOHO (in 1998), and in 2002, when the GIS rastering was discontinued.

We have selected GIS rasters with near-simultaneous EIT images and extracted average spectra. GIS data have been corrected for long-term gain depression and radiometrically calibrated using the only in-flight calibration available at this time (Del Zanna et al. 2001).

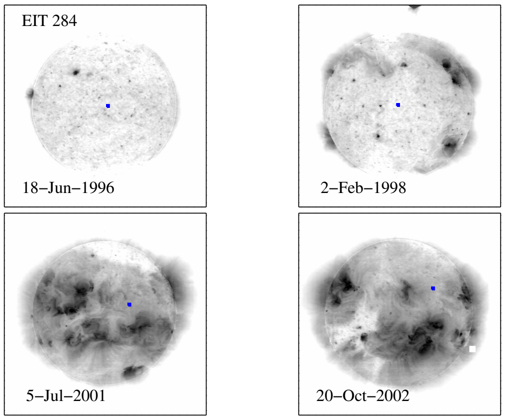

Fig. 2. EIT images (corrected for limb-brightening; same intensity scaling) in the 284 Å band. The boxes close to Sun centre show the positions of the GIS rasters.

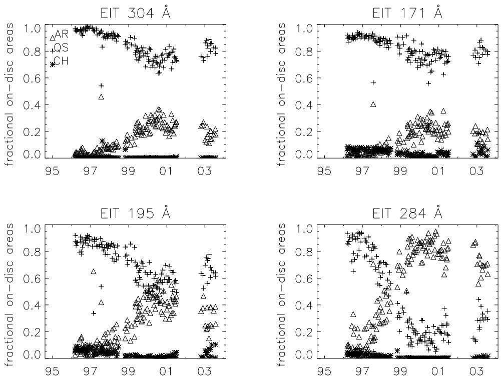

Fig. 3. Fraction of the areas covered by the different region on the solar disc; active regions (AR), quiet Sun (QS), coronal holes (CH).

We processed the EIT data using the standard SolarSoft routines.

We therefore obtained spectral measurements that can be used to directly assess the pre-flight radiometric calibration of the EIT bands (which fall in the GIS spectral regions). Fig. 5 shows as an example the observed GIS spectra folded with the EIT 284 Å responsivity, to simulate the EIT count rates. It clearly shows how the Fe XV 284 Å line dominates the band during solar maximum.

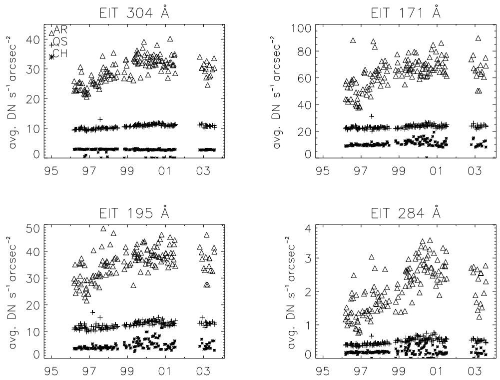

Fig. 4. SOHO/EIT averaged count rates for the different areas: active regions (AR), quiet Sun (QS), coronal holes (CH).

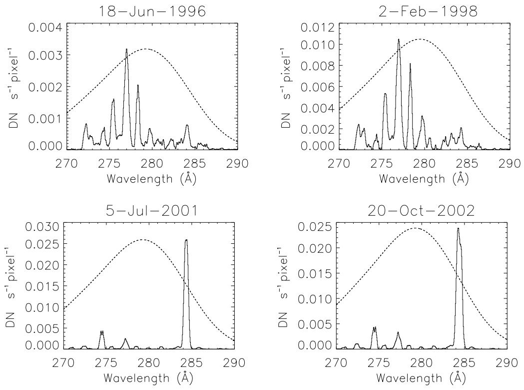

Fig. 5. GIS spectra folded with the EIT responsivity (dashed line, normalised), to simulate the count rates in the EIT 284 Å band. Note how the Fe XV 284 Å line dominates the band during solar maximum.

We have then used the SOHO/EIT images to estimate the limb-brightening correction factors to be applied to each GIS observation, i.e. to convert the quiet Sun radiances into irradiances. Especially in solar minimum conditions (1996), the limb-brightening of coronal lines is important and needs to be taken into account.

A sample of 'quiet Sun' EUV irradiances are plotted in Fig. 6. A large scatter, mostly due to solar variability (enhanced in 1999-2002) is present. The cooler lines are remarkably stable,

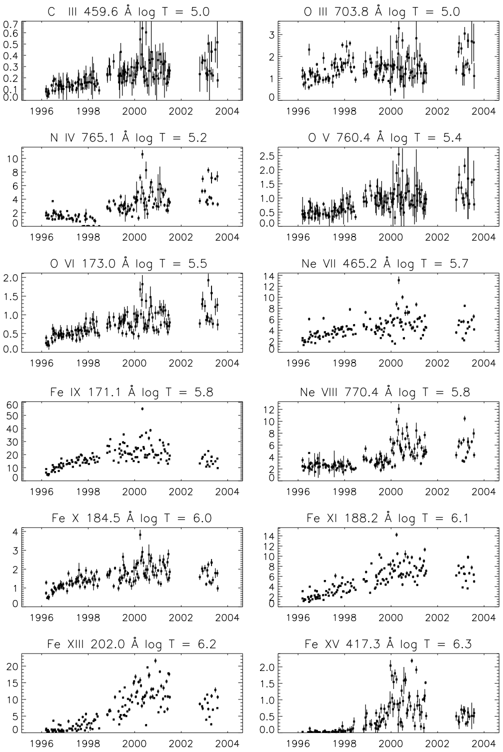

Fig. 6. EUV irradiances (10^8 phot cm^{-2} s^{-1}) of the 'quiet Sun' obtained from SOHO/GIS.

with an indication of a small increase with the cycle. On the other hand, lines that are formed above 1 MK show a pronounced increase, progressively larger for the hotter lines.

The 'quiet Sun' EUV irradiances that we have obtained for the 'quiet' period 1996-1998 compare very well with the few measurements done during 'quiet' periods in the 60's and 70's (Heroux et al. 1974), with the exception of the strong lines shortward of 180 Å, for which the SOHO/CDS irradiances are about a factor of two higher. This is likely due to an overestimation of the long-term gain depression applied to the first years of the mission.

3. Conclusions and further work

The SOHO instruments have produced a large amount of valuable data in the EUV domain. The GIS, despite a degradation due to the 1998 SOHO loss, has performed extremely well, from 1996 until now. Some refinements in the corrections to the degradation in sensitivity and in the instrument cross-calibrations are still necessary; we are however confident that the SOHO data can be used to study in detail the EUV spectral irradiance from 1996 onwards.

In this paper we have only presented preliminary results, i.e. EUV spectral irradiances of the 'quiet Sun' during 1996-2003, and some characteristics of the solar corona as seen in the EUV with EIT. The 'quiet Sun' is clearly identifiable in the histograms of EIT intensity distributions only during 1996-1998. Afterwards, the entire diffuse 'quiet' solar corona shows a different intensity distribution and spectral characteristics. GIS measurements indicate a clear increase in the radiances at all temperatures. This increase is more pronounced in lines formed just above a million degrees.

Plans for future work include detailed studies of the NIS spectra, and detailed estimates of the contribution of the active regions to the total spectral irradiance. We also plan to merge the GIS and NIS measurements to obtain EUV spectral irradiances as they vary with the solar cycle.

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