The EUV spectrum of the Sun: SOHO CDS NIS radiometric calibration

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Received ; accepted

ABSTRACT

We present SOHO Coronal Diagnostic Spectrometer (CDS) Normal Incidence extreme-ultraviolet spectra of the Sun taken from the beginning of the mission in 1996 until now. We use various methods to study the performance of the instrument during such long time span. Assuming that the basal chromospheric-transition region emission in the quiet parts of the Sun does not vary over the cycle, we find a slow decrease in the instrument sensitivity over time. We applied a correction to the NIS (Normal Incidence Spectrograph) data, using as a starting reference the NIS absolute calibration obtained from a comparison with a rocket flight in May 1997. We then obtained NIS full-Sun spectral irradiances from observations in 2008 and compared them with the EUV irradiances obtained from the Apr 2008 rocket which flew a prototype of the Solar Dynamics Observatory EVE instrument. Excellent agreement is found between the EUV irradiances from NIS and from the EVE-prototype, confirming the NIS radiometric calibration. The NIS instrument over 13 years has performed exceptionally well, with only a factor of 2 decrease in sensitivity for the long-wavelength channel, with the exception of the strongest lines. The short-wavelength channel suffered badly during the period of SOHO loss.

Key words. Sun: corona – Techniques: spectroscopic

1. Introduction

The SOHO Coronal Diagnostic Spectrometer (CDS) is composed of a Normal Incidence (NIS) and a Grazing Incidence (GIS) Spectrometer (Harrison 1995). CDS covers, with a few minor gaps and 9 channels, the important 150-800 Å EUV spectral range. CDS has routinely operated from 1996 to now, and is providing us the opportunity for the first time to study extreme-ultraviolet (EUV) radiances and irradiances along a full solar cycle, from 1996, during the previous solar minimum of activity to now.

Before any study is performed, a full analysis of the performance of the instrument during such long time span is needed. In particular, it is fundamental to characterise the radiometric calibration as a function of time, which is the main aim of this manuscript. A significant effort to obtain the radiometric calibration of the CDS instrument was devoted during the first 2 years of the mission, 1996-1997.

The 'standard' CDS calibration available through SolarSoft is based on a comparison between the EGS rocket flight of 1997 May 15 (Woods Rocket) and CDS/NIS FULL SUN NIS spectral radiance measurements. It is described in Brekke et al. (2000). This study produced *absolute* values of the in-flight NIS sensitivities, for both NIS 1 and NIS 2. For NIS 2, it was possible to estimate a coarse wavelength-dependence. For NIS 1, only one reliable measurement at 368 Å was possible.

Del Zanna et al. (2001) obtained an independent radiometric calibration for all the GIS and NIS channels by studying line ratios in a large number of observations (on-disc, off-limb, quiet sun, active region). The observed line ratios were compared to theoretical and/or previously well-calibrated measurements, to obtain the relative sensitivity between all the 9 spectral ranges (6 in first order and 3 in second). The Del Zanna et al. (2001) radiometric calibration was obtained relative to the responsivity at 584 Å. Once the Brekke et al. (2000) responsivity at 584 Å is adopted as a reference, the Del Zanna et al. (2001) and the 'standard' calibrations agree within 30% or so, which is satisfactory. After two workshops held at ISSI (cf. Del Zanna 2002, and the book 'The radiometric calibration of SOHO'), the teams of the various instruments on-board SOHO converged to a consistent relative radiometric inter-calibration within 30-50%, at few selected wavelengths.

The study of the long-term ageing of each of the SOHO instruments has taken a considerable amount of years and efforts. After many attempts, we realised that the performance of the GIS was best obtained by studying the synoptic radiance measurements of the quiet Sun and the behaviour of line ratios. The final results, published in Kuin & Del Zanna (2007), were that for many wavelengths no appreciable drop in sensitivity was present. The strong lines were however affected by gain depression.

After testing various methods over the last few years (see, e.g. Del Zanna et al. 2005; Del Zanna & Andretta 2006), we also resorted in using a similar approach to characterise the NIS performance. Some of the previous attempts were based on comparisons between NIS irradiances and those obtained with the TIMED SEE EGS Woods et al. 2005 instrument. The TIMED SEE EGS irradiances were calibrated with three EGS rocket flights flown in 2002,2003, and 2004. The NIS-EGS comparisons indicated the need to revise the radiometric calibration of TIMED SEE EGS irradiances, a work which is in progress.

The methods we adopted basically rely on the assumption that the basal chromospheric-transition region emission in the quiet parts of the Sun does not vary over the cycle. There have been some reports which appear to contradict this, based on SOHO SUMER radiance measurements (e.g. Schühle et al. 2000; Pauluhn & Solanki 2003). However, the large solar variability in small fields of view and the large uncertainties in the in-flight radiometric calibration have left some doubts about these results.

As it is often the case, it was only thanks to long-term ground-based measurements that this issue could be clarified. Ground-based measurements of equivalenth widths of photospheric and chromospheric lines (e.g. Ca II) over the 'quiet Sun' (often Sun centre) have in fact provided good evidence that the basal photospheric-chromospheric emission has not changed over the last three solar cycles (Livingston et al. 2007). Note that these types of measurments are independent from calibration issues, hence are very reliable.

Fortunately, on April 2008, the prototype of the Solar Dynamics Observatory EVE instrument was launched on-board a rocket. It provided an excellent EUV spectrum (Woods et al. 2009; Chamberlin et al. 2009). The prototype instrument was radiometrically calibrated at NIST, and has a much higher spectral resolution compared to the TIMED SEE and the previous rocket flight instruments, but very similar to that one of the NIS. We could therefore use these rocket data to check the NIS radiometric calibration.

2. The NIS instrument and the synoptic radiance observations

The CDS instrument consists of a Wolter-Schwarzschild type II grazing incidence telescope, a scan mirror, and a set of different slits. The NIS is composed of two normal incidence gratings that disperse the light into the NIS detector, mainly composed of a microchannel plate (MCP) and a charge coupled device (CCD) known as the viewfinder detector subsystem, or VDS. The gratings are slightly tilted, in order to produce two wave-bands (NIS 1: 308 – 379 Å and NIS 2: 513 – 633 Å).

The temporary loss of contact with SOHO in June 1998 damaged permanently the performance of some of its instruments. The spacecraft was successfully recovered in September 1998. The NIS post-recovery spectra present broadened and asymmetrical line profiles, that in particular for NIS 1 strongly reduce the spectral resolution. The spectral resolution in terms of full-width at half-maximum (FWHM) was $\simeq 0.35$ Å for NIS 1 and $\simeq 0.5$ Å for NIS 2 pre SOHO-loss.

MCPs normally suffer a drop in gain due to the exposure to solar radiation. For the NIS, this results in a depression at the core of the lines (the so-called *burn-in* of the lines), that is non-negligible for the brightest lines. This effect in the NIS spectra has been monitored since launch with the NIMCP study, as described in Thompson (2000) (also see below).

The use of the wide 90″slit (number 6) also causes with time a drop in the NIS sensitivity. Contrarily to the line core burn-in, this kind of efficiency loss affects wide regions of the detector. A preliminary 'CDS standard correction' for the observed drop in count rates in time assumed that the main factor in the drop of the sensitivity was due to the use of the wide 90″ slit. This standard correction has been used until now within the standard analysis software, and is described in Thompson (2006). The method assumed firstly that the He I 584 Å radiance of quiet Sun regions should be constant with time. Radiances from the long-term SYNOP (Sec. 2.3) data were used. This preliminary correction turned out to be quite accurate up to 2003, when observations were analysed. For later dates, an extrapolation was adopted, which turned out to overestimate the correction by up to a factor of 2.

A preliminary correction for the other NIS wavelengths was then estimated by obtaining an average normalised wide slit spectrum, and scale the corrections for the other wavelengths by assuming that the burn-in would follow this wide slit spectrum. The time dependence of the scale factor was derived from an estimate of the total number of photons recorded by the instrument over time. Ideally, one could actually count the number of photons recorded by the instrument over time. In reality, however, only the data pertaining to a few spectral windows are routinely telemetered to the ground, so it is impossible to recover the history of light exposure.

So, in practice, it was assumed by Thompson (2006) that the accumulated photon count on the detector is proportional to the estimated accumulated exposure time. Such an assumption, however, would be valid only if the 90″ slit was used to observe quiet regions only. This is likely to be not true, as the significant loss of sensitivity in the NIS1 regions around the position of the Fe XVI 335 and 360 Å lines indicates. These lines become in fact the prominent lines in active region spectra, and the NIS1 spectra show an increasing depression with time at these wavelengths.

The assumption that the drop of the sensitivity has been mainly due to the use of the wide 90″ slit predicts that the regions in the detector where the strongest lines fall should show a progressive decrease in sensitivity, something which the data, with the exception of the Fe XVI 335 and 360 Å lines, do not show as we shall see below.

The NIS instrument has obtained various types of routine radiance measurements over the years which we have used to study the instrument's performance. The NIS provides radiances over a maximum field of view of 4′×4′ by moving the scan mirror to produce contiguous images of one of the long slits (a 'raster'). Telemetry constraints are such that only a small fraction of the data recorded onboard are telemetred to the ground.

Routine radiance measurements over the quiet Sun have been taken with various programs. Here we focus on the daily NIMCP 'study' (Sec. 2.2). Daily synoptic radiance observations in a few spectral windows have been taken regularly in a strip along the meridian with various variants of the CDS study SYNOP (Sec. 2.3). Radiance measurements over the whole Sun have been taken quite regularly once a month or so after 1998 with the CDS study USUN (Sec. 3). They consist of 700-1000 single slit exposures sampling the whole Sun in about 13 hours (see, e.g., Thompson & Brekke 2000 for details).

2.1. Data analysis

The bias of the CCDs is regularly monitored. We have applied standard processing for the de-biasing and flat-fielding, using the CDS routine VDS_CALIB. Cosmic ray hits strongly constrains NIS observations, in the sense that exposure times cannot be too long. Cosmic ray hits have been removed from the subsequent analysis. Many geometrical distortions of the NIS spectra are present (see, e.g., Haugan 1999). The main one is the slant in the spectra, i.e. the fact that the dispersion direction is not parallel to the CCD rows. This has been corrected for by the CDS routine VDS_ROTATE.

NIS spectra contain a wavelength-dependent scattered light ('background') component, which is mostly concentrated in the network areas, but disappears in off-limb observations. The NIS1

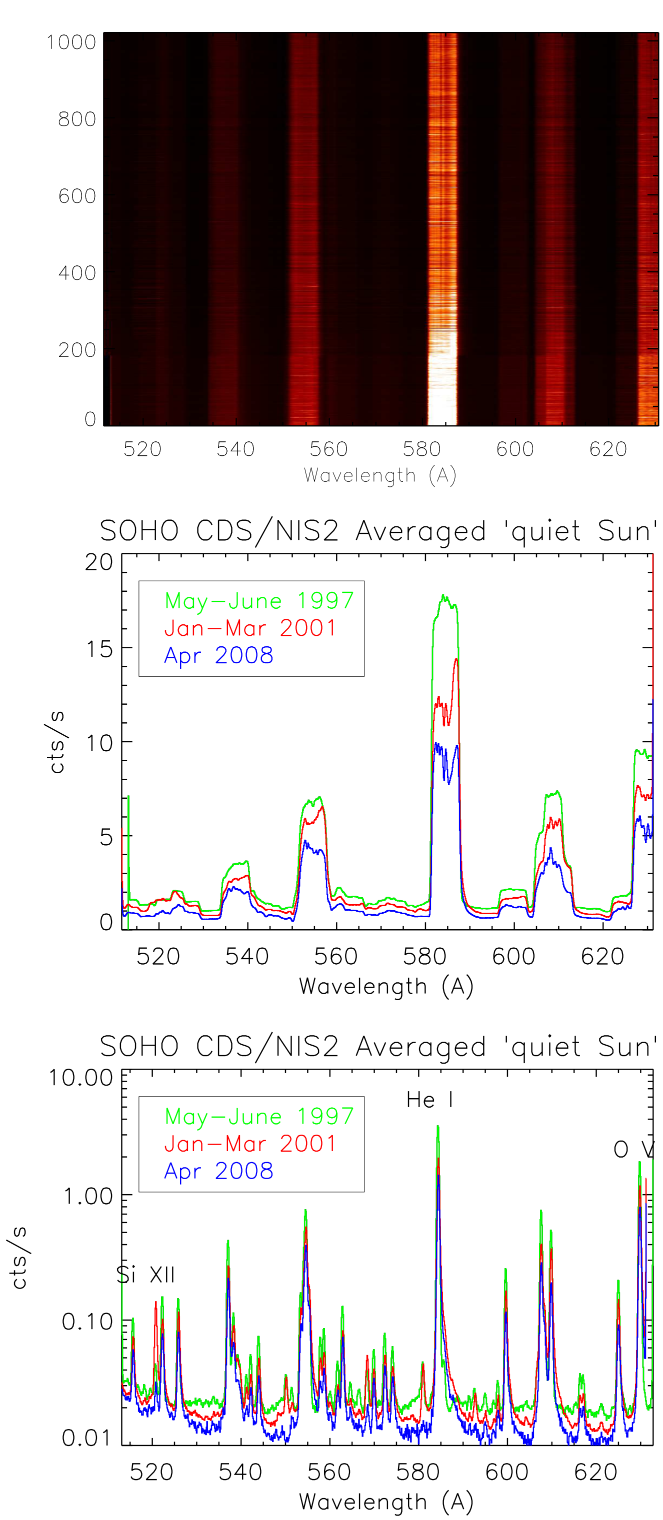

Fig. 1. Top: image of the 13 years of NIMCP 90″data over the quiet Sun. Middle: a sample of averaged 90″ spectra at three different epochs. Bottom: the corresponding 2″ spectra. Notice the overall decrease in the count rates in both 2,90″ spectra.

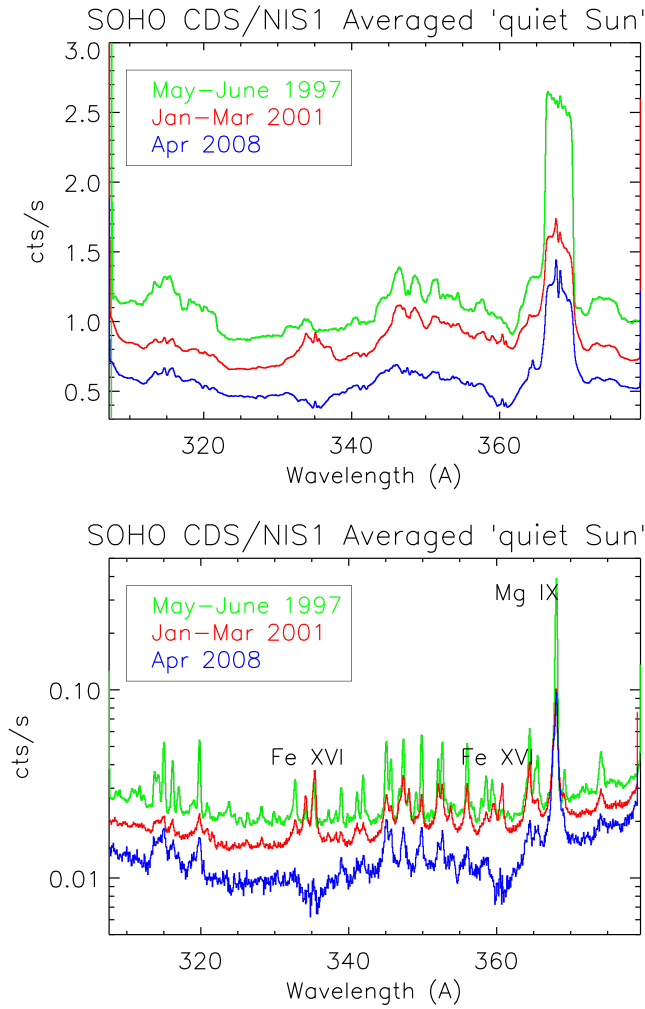

Fig. 2. Averaged spectra from the NIMCP 90,2″ quiet Sun observations for the NIS1 channel.

is mostly affected. It is believed that most of this scattered light is due to the H I Lyα.

2.2. NIS MCP test (NIMCP)

The NIMCP standard observations consists of a sequence of narrow 2″ (number 4) and wide 90″ (number 6) slit exposures over a quiet Sun region. NIMCP data have been corrected for bias, cosmic rays, flat-field, geometrical distorsions (slant in the spectra). For each exposure, spectra have been averaged along the slit.

For the 2″ data, the burn-in in the core of the lines was corrected for by reconstructing the line profiles. This is done with good accuracy (typically a few percent for some lines) as described in Thompson (2000). The corrections applied by the standard CDS software were obtained from the analysis of data up to 2003. An extrapolation is then applied. We have checked the correction for the strong lines, which appears to be accurate to within a few percent. Fig. 1 shows the entire averaged 13 years of NIMCP 90″data over the quiet Sun corrected for the narrow slit burn-in. A few exposures with too low or too high count rates were manually removed from the data set, leaving over 1000 averaged spectra. The same Fig. 1 also shows three averaged spectra, taken near the beginning of the mission (May-June 1997), after SOHO loss during solar maximum (Jan-Mar 2001) and recently in Apr 2008. Notice the overall decrease in the count rates in both 2,90″ spectra.

The drop in coun rates is more evident in the NIS1 channel, as Fig. 2 shows. Notice the presence of the Fe XVI 335 and 360 Å lines during solar maximum, even in these 'quiet Sun' observations, and the large drop in count rates in both 90,2″ spectra around these lines. Alo notice the large broadenings in the NIS1 lines, occurred during SOHOloss.

The 90″ slit 'smoothes out' the solar radiation, making it a good candidate to study the overall decrease in sensitivity. Furthermore, almost all of the strong lines in the NIS2 channel are formed at low temperatures, and have radiances expected to be constant over quiet Sun regions. Large parts of the NIS1 channel are also dominated by transitions formed at temperatures at or below 1 MK, so large solar variability effects are not expected.

(VA) I think there should be a figure showing the bands in slit 6 spectra used to determine the decay of detector efficiency.

We therefore partitioned the NIS1,2 channels in wavelength bands centred on the various dominant lines, and obtained averaged count rates from the the 90″ slit as a function of time. They are shown in Figs. 3,4. The vertical dashed lines mark a few significant events: the first VDS exposure (January 1996); the first NIMCP data set analyzed (May 1996; taken as reference for our subsequent analysis); the date of loss of contact with SOHO (June 1998), and the return of SOHO to its normal mode (September 1998).

The data points have been binned over a 90 days period, obtaining an estimate of the mean and standard deviation in each time bin (points with error bars). These binned data were then fitted with a linear (before June 1998) or quadratic (after September 1998) polynomial in logarithmic scale (thick line in the figures). These curves were then taken as our best estimate of the efficiency loss in each given band, and obtained from them the relative corrections.

To check the validity of the approch, we applied these corrections to three other independent datasets. Firstly, to the count rates in the NIMCP2″ slit data. All the lines in the NIS2″ slit spectra were fitted with simple Gaussian profiles for the pre-SOHO loss, and broadened profiles after. The un-corrected count rates show the same trends as those of the 90″ slit data, i.e. an overall drop of about a factor of two over 13 years. Once the corrections are applied, most lines show a constant trend. A sample is presented in Figures 5 and 6. All the lines show a large scatter, due to solar variability, but no particular trends. Many of the weaker lines (e.g. He I 522.21 Å, O IV 608.4 Å) show some residual trends, which in most cases are due to the effects of strong nearby lines. The lines formed at temperatures higher than 1 MK (e.g. Si XII 520.6 Å and Fe XVI 335.3 Å) do show much higher counts during the period of solar maximum (2000–2003). We then applied the corrections to the daily synoptic observations as described below.

2.3. Daily synoptic observations (SYNOP)

NIS has observed with daily cadence a strip of the Sun along the meridian with 9 4′×4′ rasters with the 2″ slit – study SYNOP. Different versions of this study have been run over the years, with different line selection. However, all of them included the two brightest lines, the He I 584 Å and the O V 630 Å. These lines are formed at chromosphere-transition region temperatures, and are therefore less affected by the solar cycle. Indeed they are the only lines that could be used for our purposes. Other lines either had low count rates or were too broad for the narrow extraction windows.

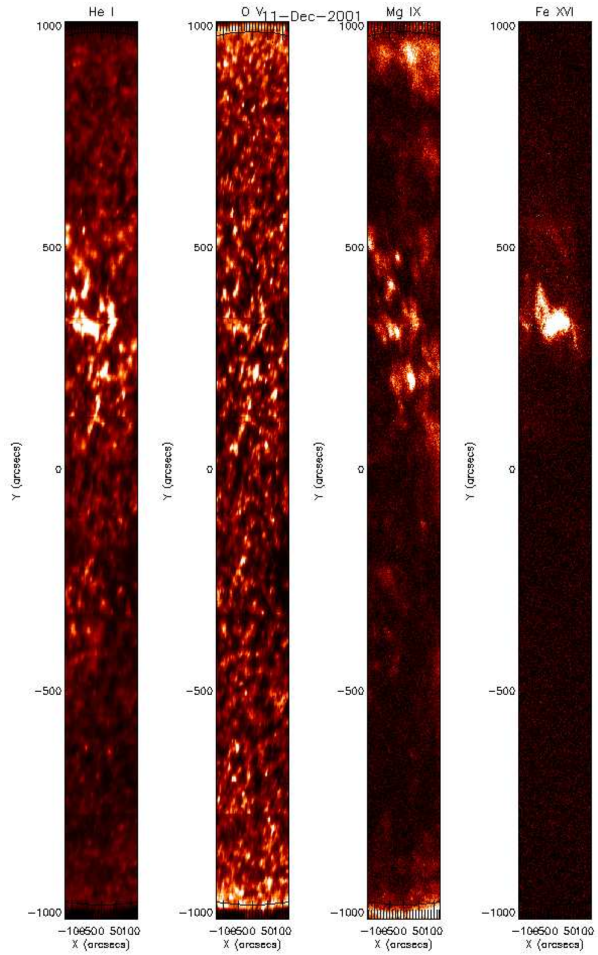

Fig. 7. Mosaics of NIS radiances in a few spectral lines observed with the SYNOP program along a strip centred on the meridian.

We have selected a (relatively small) sample of synoptic observations spanning the 13 years of SOHO operations, trying to uniformly cover the whole period but at the same time trying also to avoid days when strong active regions dominated. We have processed the NIS data by applying the standard corrections for the bias, flat-field, cosmic rays, and 2″ slit burn-in.

We have then applied the Del Zanna et al. (2001) radiometric calibration ???

We have then, with custom-written software, created mosaics of the 9 rasters, by checking the alignment and by averaging the strips where overlap between successive rasters is present (Fig. 7).

Since we are interested in the properties of the quiet Sun radiances, we did not consider data beyond 0.8 $R_{\odot}$, thus removing limb-brightening effects and, above all, avoiding the polar regions, which, especially during the minimum, are severely affected by the presence of coronal holes. From these mosaics, histograms of radiances were derived for each of the lines in the study (Fig. 8). We note that this is the first time that a study of radiance distributions along a cycle has been possible.

At the low temperatures of formation of He I, O V, these distributions, over quiet regions, appear remarkably stable and have a log-normal distribution. The presence of such a distribution is

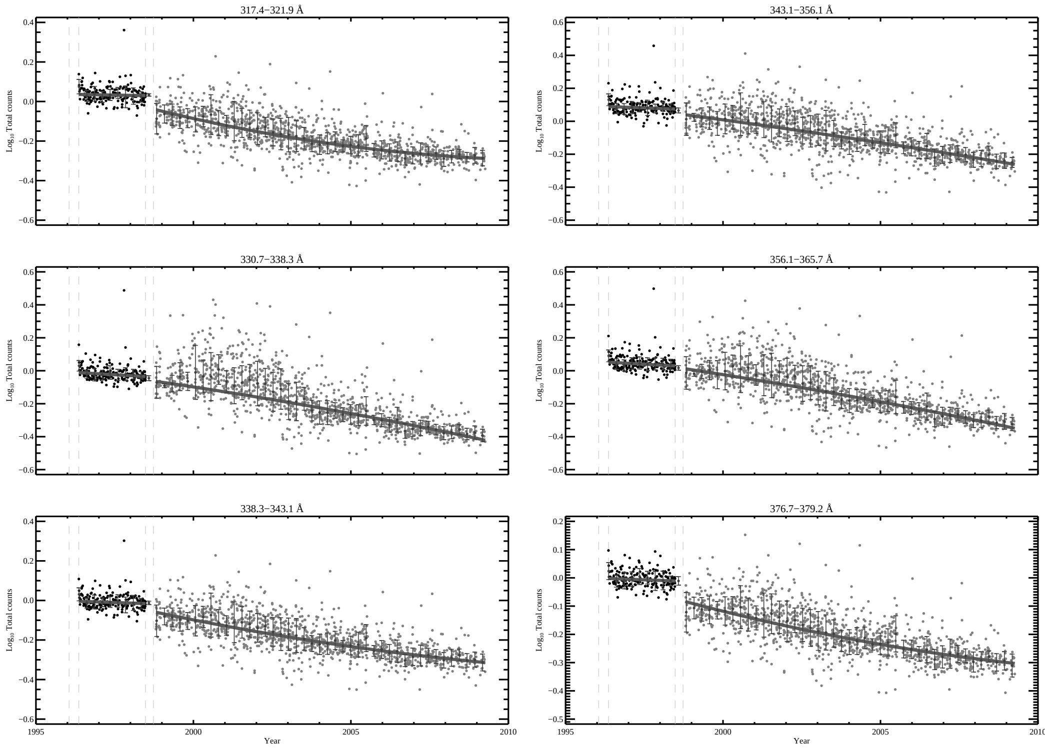

Fig. 3. Time-dependence of average radiances in various wavelengths from NIMCP 90″quiet Sun observations in the NIS1 channel.

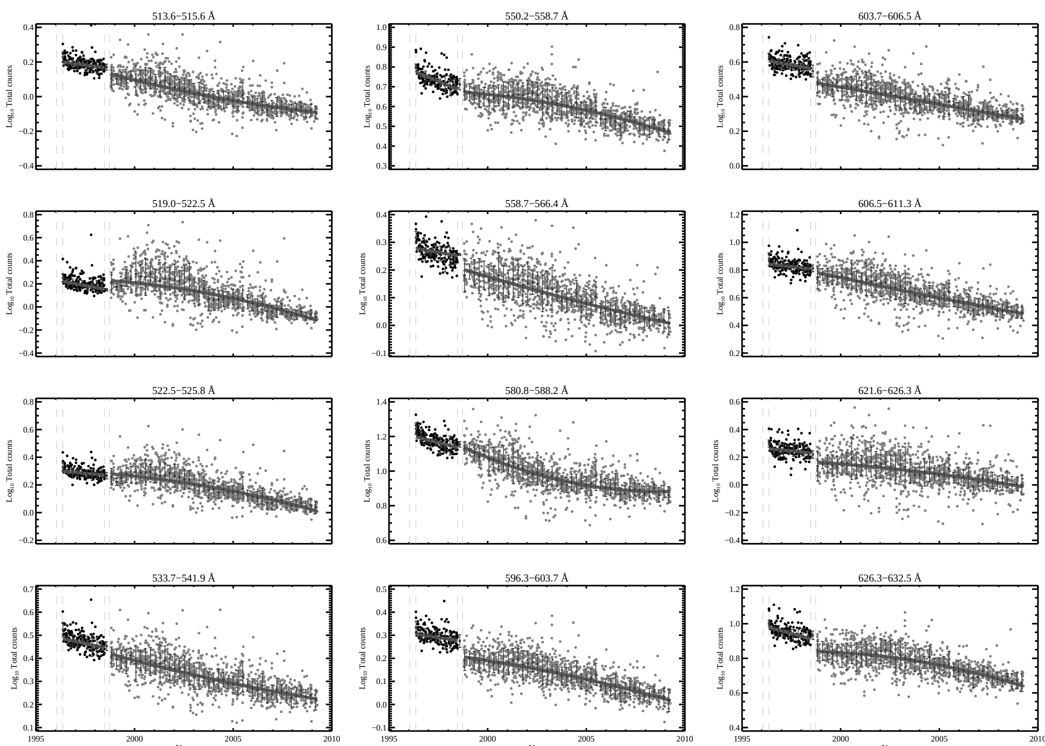

Fig. 4. As Fig. 3, but for NIS2 channel.

not new, as it was found, e.g., in Skylab data **(REF)** and more recently "rediscovered" in SOHO data **(REF: Wilhelm ?)**.

In order to evaluate the variability with time of the center of the log-normal distribution, we chose to estimate the "mode", or the peak of the radiance distribution in the CDS rasters away from the poles, via a gaussian fit of the core of the distribution (which also provides an estimate of its width). We found this statistical estimate to be less sensitive than the mean or the median to the distorsion of the distribution due to active regions (on the higher-radiance side) or to the occasional equatorial coronal hole (on the lower-radiance side).

Fig. 9 therefore shows estimates of the "quiet Sun mean radiance" at disk center: the effect of possible active regions or

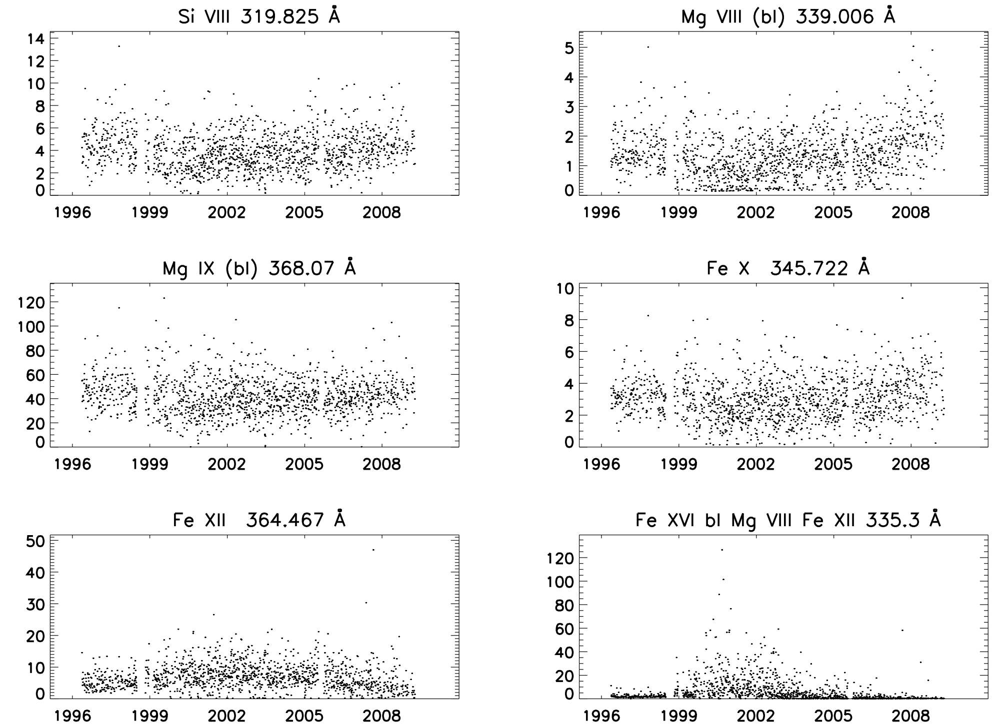

Fig. 5. Line radiances (units are photon-events) from NIMCP 2″quiet Sun observations in the NIS1 channel after applying the sensitivity correction.

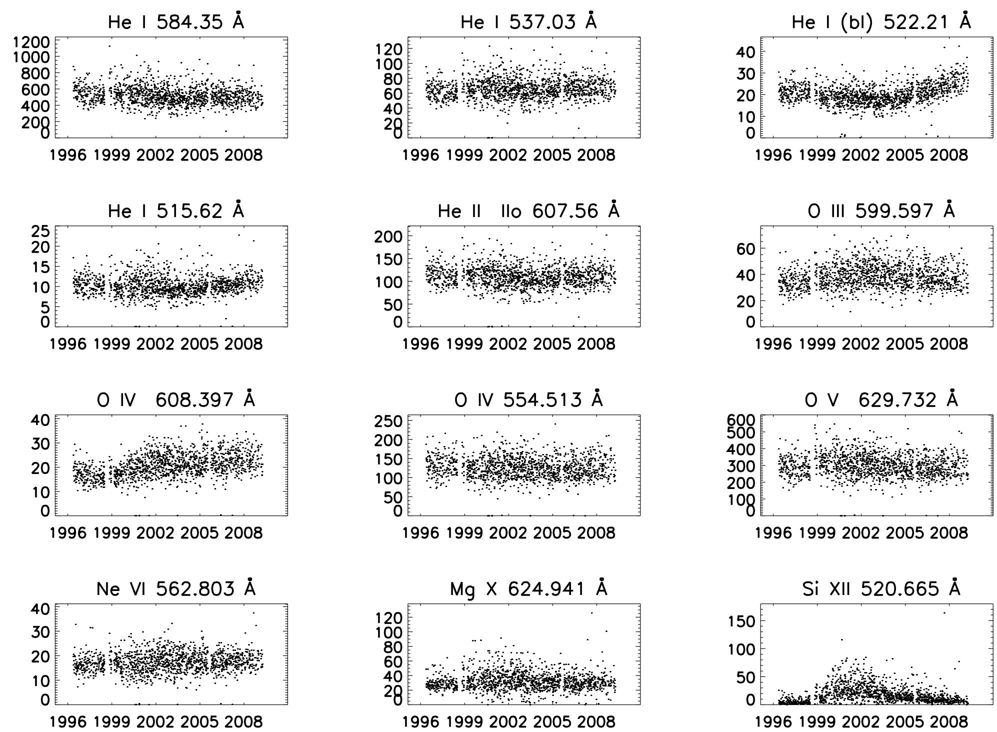

Fig. 6. Line radiances from NIMCP 2″quiet Sun observations in the NIS2 channel, as in Fig. 5.

equatorial coronal holes crossing the meridian is small. Hence, there should be little or no influence on those radiances from solar cycle variations (except, of course, from possible, "intrinsic" variations in the quiet Sun itself.)

Ignoring the drop in NIS sensitivity would produce a marked drop in mean quiet Sun radiances with time (open circles in Fig. 9). The "standard" correction currently available for this effects, while adequate for the weaker O V line, would however result in a steady increase of He I radiances (filled circles). This latter effect is also apparent by comparing the histograms in Fig. 8 obtained at two differents epochs.

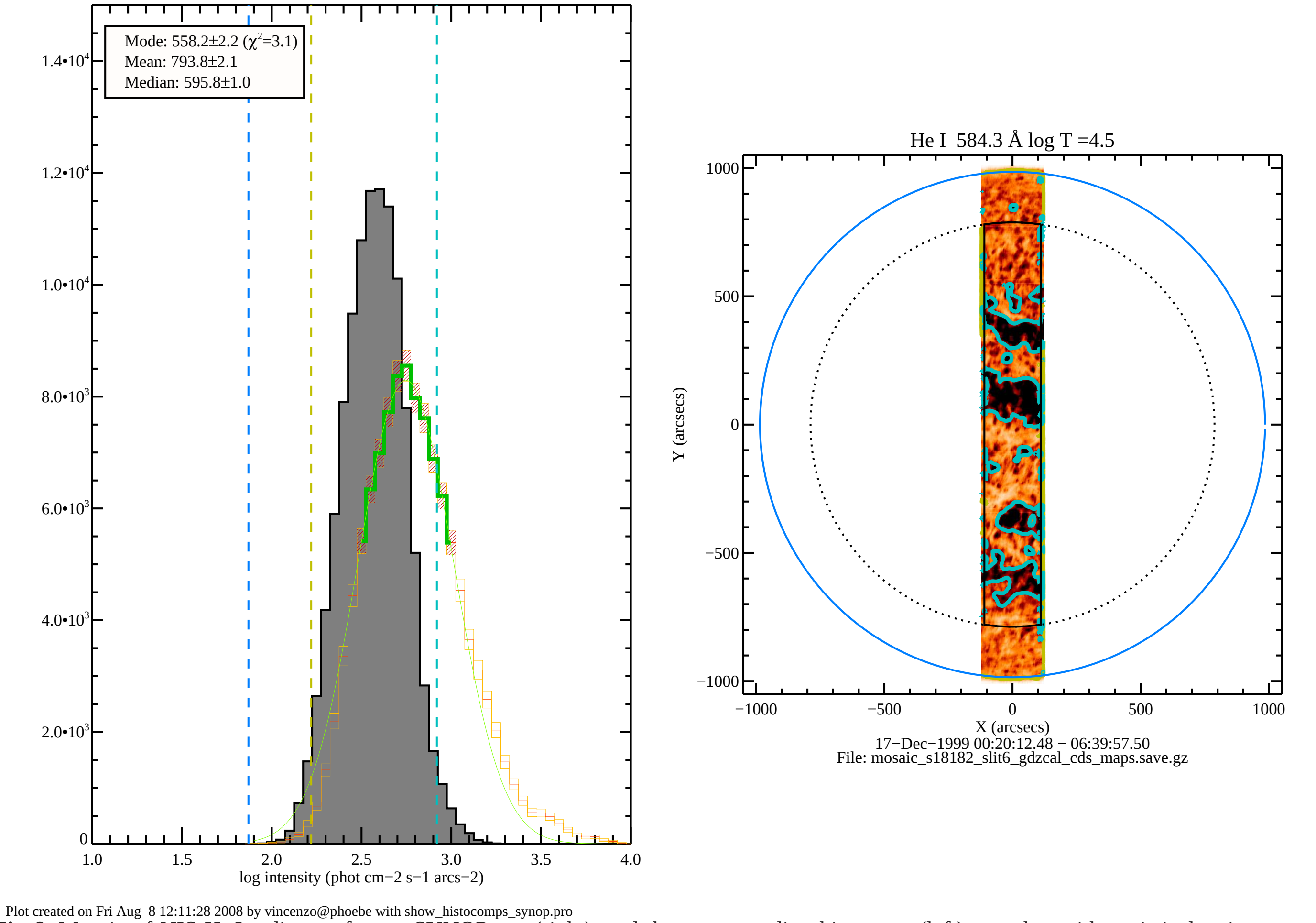

Fig. 8. Mosaic of NIS He I radiances from a SYNOP run (right), and the corresponding histogram (left), together with statistical estimators of its center and width. The vertical dashed lines in the left-hand panel indicate the levels of contours on the right-hand image. The grey-shaded histogram represents the analogous SYNOP run of June 18, 1996.

The correction we derived *indipendently* from NIMCP data (Sec. 2.2) does instead produce radiances in the current minimum consistent with the previous one (starred symbols in Fig. 8). We also found that the widths of the log-normal histograms are also similar during the two minima of solar activity.

3. NIS irradiances compared to those from the EVE prototype

On the 14th of April 2008, the prototype of the Solar Dynamics Observatory EVE instrument was launched on-board a rocket and produced an excellent EUV spectrum that we have used as a final check on the NIScalibration.

The USUN study consists of 69 rasters covering the whole Sun (with some off-limb coverage). The movement of the slit is 'sparse' in the sense that the 4″ slit is moved in stpes larger than its width. The total radiance of the Sun is therefore subsampled by about a factor of 6. Exposures are also binned on-board along the slit, to increase the count rates and reduce the telemetry load.

The NIS rasters do not observe the whole off-limb corona to great distances. As part of the analysis work in preparation for a follow-up paper, we have also constructed mosaics of the NIS radiances, and studied the off-limb behaviour of all the lines in the NIS spectra, to estimate of the off-limb contribution which was not observed. For lines formed at chromosphere-TR temperatures, such as the majority of lines in the NIS 2 channel, this is usually less than 1%.

No NIS full-Sun observations during the EVE prototype rocket flight were scheduled, so a direct co-temporal comparison is not possible. However, fortunately, the level os solar activity has been extremely low and a 'featureless' Sun was typical for most of 2008. We have done a preliminary analysis of many NIS full-Sun observations and we have indeed found that spectral irradiances have been very constant. In particular, we have processed the NIS full-Sun NIS irradiances obtained before (2008 March 17) and after (2008 May 26) the 2008 April 14 rocket flight and found differences only to within a few percent. For the following, we only consider the spectra of 2008 March 17.

We have corrected the USUNdata for bias, cosmic rays (with a specially-written software), flat-field. We have then obtained the radiances in all the lines, and constructed a mosaic of the rasters to check for accuracy of the pointing. We have then linearly interpolated the spectra in the spatial domain, and then summed them. We have then applied the Del Zanna et al. (2001) radiometric calibration. Finally, we have applied the wavelength-dependent corrections for the sensitivity drop.

The resulting spectra are shown in Fig. 10 (black line) alongside the spectrum from the EVE prototype (red line). The NISscattered light has been removed by subtracting a fixed amount at all wavelengths. Indeed, the scattered light doe not appear to have any wavelength-dependence in the raw spectra,

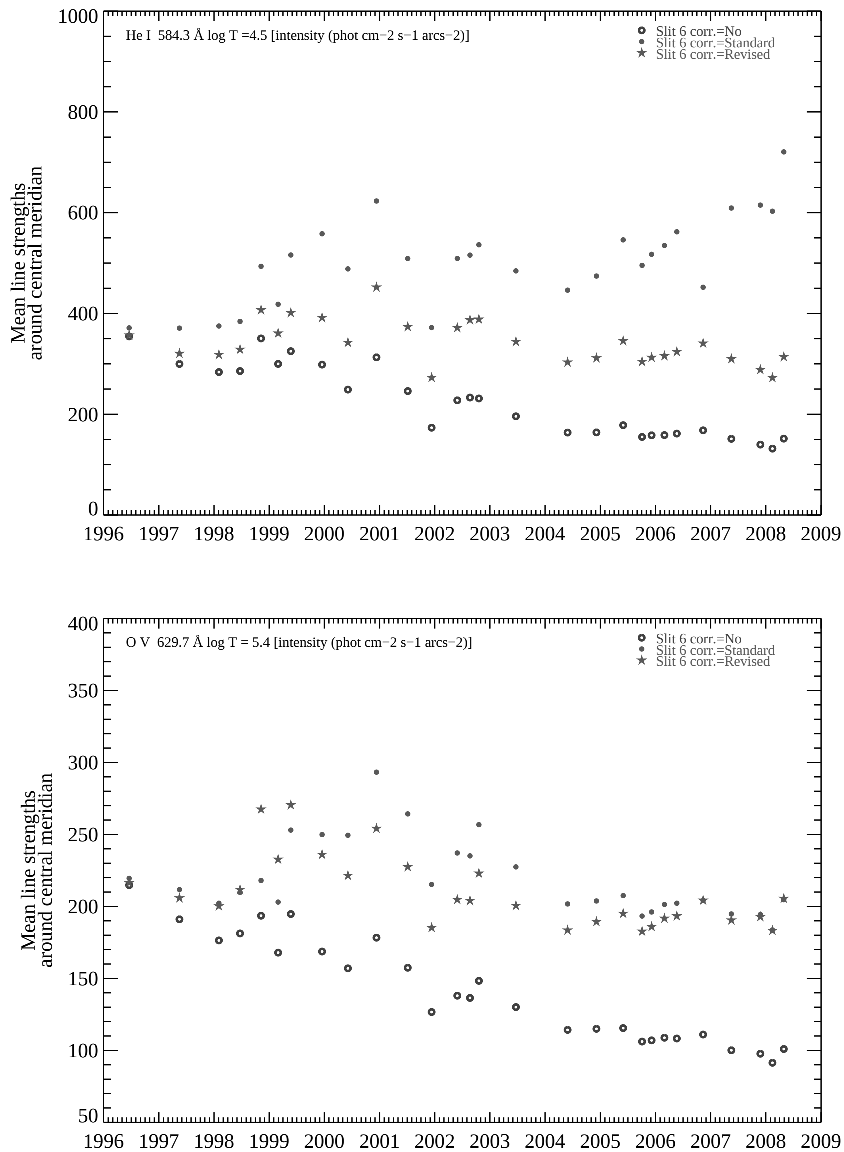

Fig. 9. Radiances of He I (top), O V (bottom) with and without the correction for gain depression.

with the exception of the lower and higer parts of the NIS1 channel. Notice that the large increase in the NIS1 spectrum at lower wavelengths is mostly due to the way the responsivity changes (Del Zanna et al. 2001).

The overall agreement between the NISand EVE prototype spectra is excellent. In the NIS2 channel, the spectral resolution of the EVE prototype is slightly lower, but all the main lines observed by NISare also seen there. Note that the He II 304 Å line observed in second order with NISis not present in the EVE prototype spectrum (however this line, blended with Si XI, is observed in first order). The comparison between the NIS1 and the EVE prototype is also very good. Here, the EVE-prototype spectral resolution is also lower, but the lines in the NIS1 channel are so broad that any measurement is very difficult.

To provide a quantitative comparison, all the spectral lines have been fitted, those in the EVE prototype with Gaussian profiles, while those in the NISspectra with broadened profiles (which have been developed by WTT). The larger uncertainty in the fit is the location of the background for the scattered light, in particular for the NISchannel. The fitting in the NISspectra was done on the spectra in photon-events, where the scattered light component is more constant. Then, the Del Zanna et al. (2001) calibration was applied to the data. The NISirradiances of lines which are blended in the EVE spectrum have been summed. These NISvalues are shown in Fig. 11 as triangles, together with the values from the EVE prototype spectrum (diamonds). The overall difference of about a factor of 2 is evident. We have then applied the correction for gain loss found here (boxes) and the ’standard’ one (stars). An indicative uncertainty of 30% (Del Zanna et al. 2001) is also shown. With few exceptions, extremely good agreement is found, if one considers the various cumulative uncertainties. Very good agreement is found for the strongest line in the NIS1 channel, the Mg IX 368 Å line. Differences in the other lines are partly due to the uncertainity in the background subtraction.

Very good agreement for most NIS2 lines is found, with the notable exception of the two strongest lines, the He I 584 Å and O v 630 Å lines. Historical measurements of the irradiances of

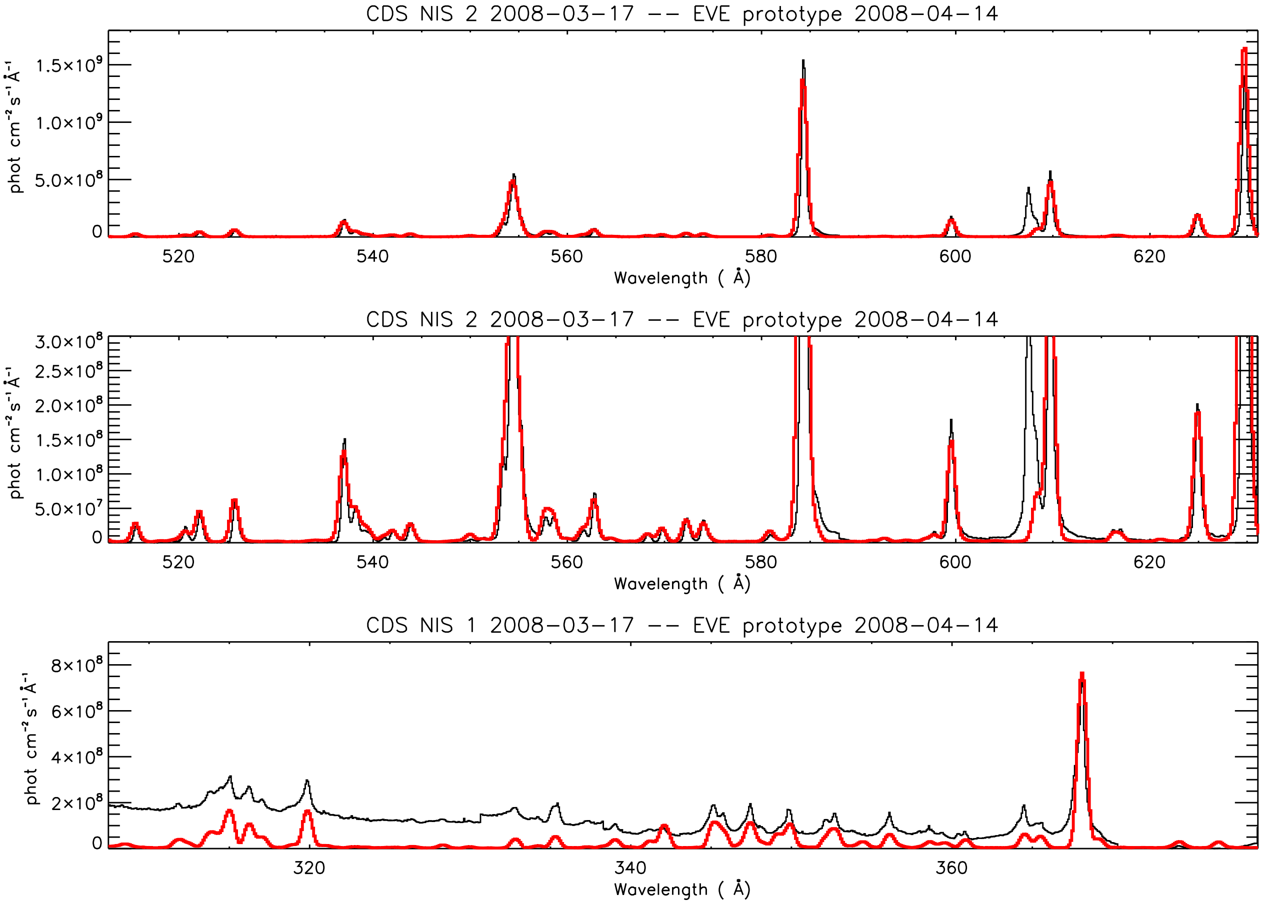

Fig. 10. Spectral irradiances from the NISUSUNspectra (black) and from the EVE prototype. The NISdata have been radiometrically calibrated with the Del Zanna et al. (2001) responsivities, and corrected for the loss of gain depression.

these two lines go back to the 1960's. These measurements suggest that the EVE irradiances of these two lines are slightly overestimated, in particular the O v 630 Å line. Another likely explanation for the disagreement is an overall 20% underestimation of the irradiances in the 1997 May 15 (Woods Rocket) spectrum. Indeed, almost all the NIS2 irradiances are consistenly lower than those from the EVE-prototype spectrum.

4. Conclusions

The NIS instrument over 13 years has performed exceptionally well, with only a factor of about 2 decrease in sensitivity. The NIS2 channel is still providing excellent spectra, however the NIS1 suffered badly during the period of SOHO loss. Future instruments such as the planned spectrometer for Solar Orbiter should have MCPs, so it is reassuring to see such a good performance over such a long time.

A coordinated calibration program for the CDS instrument has been lacking. A few rocket flights (e.g. EUNIS) were launched, but only provided limited information.

The various NIS synoptic programs have been very useful for the study of the long-term sensitivity changes. We were able to obtain a time-dependent calibration which showed good agreement (to within 30%) with the iradiance measurements from the SDO EVE prototype, with the exception of the He I 584 Å and O v 630 Å lines, where disagreemnt is slightly larger. Further work is in progress to shed light into this issue.

Nevertheless, considering the various cumulative uncertainties, we consider that providing a time-dependent absolute radiometric calibration which compares well, to within 30%, after a period of 13 years of operation is a considerable achievement.

Acknowledgements. GDZ acknowledges support by STFC (UK) through the Advanced Fellowship program.

The results obtained here could not have been achieved without the efforts of a large number of operation and scientific staff which have successfully run the CDS instrument at RAL and GSFC.

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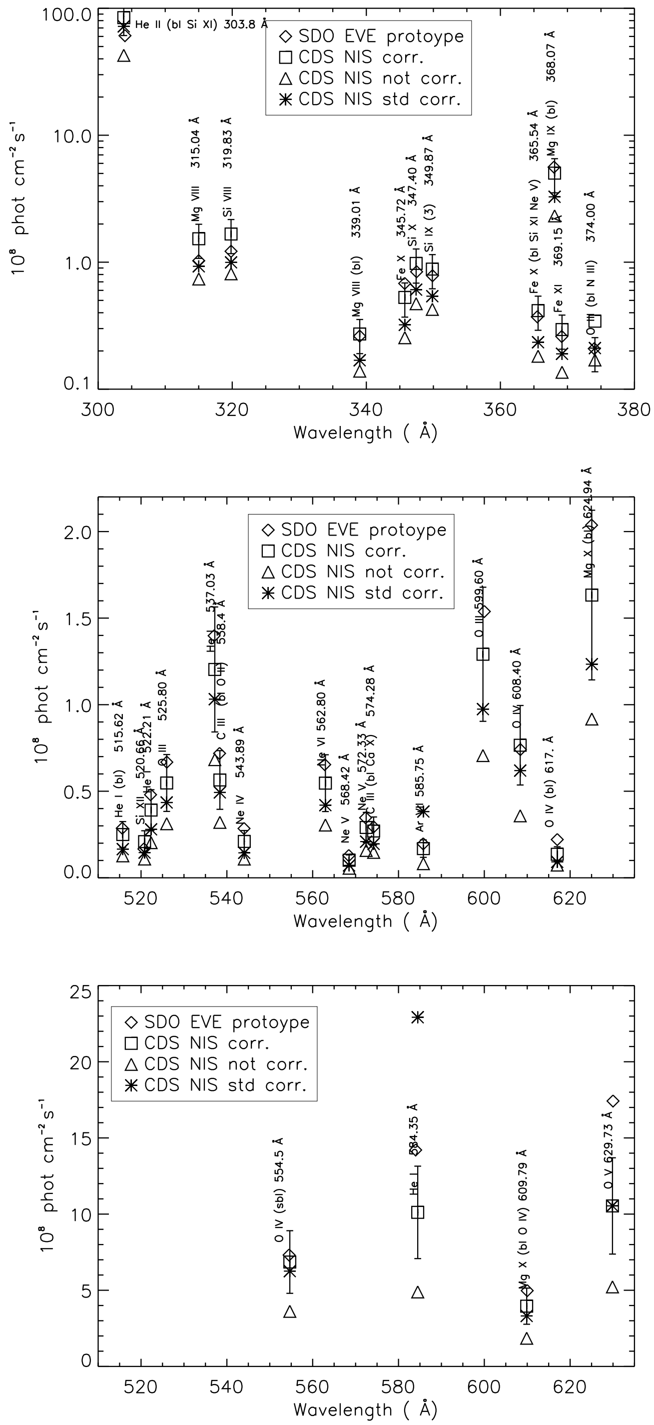

Fig. 11. Line irradiances from the NISUSUNspectra and the SDO EVE prototype (diamonds). NISirradiances obtained with the Del Zanna et al. (2001) radiometric calibration are shown with triangles. We then applied the correction for gain loss found here (boxes) and the 'standard' one (stars).

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