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The Use of Atomic Data for the In-flight Calibration of the CDS Spectrometers

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I describe a general method that has been used for the in-flight cross-calibration of the CDS spectrometers. This method relies on accurate atomic data and uses the Sun as a 'calibration' source. It was successfully applied in the past to calibrate other EUV spectrometers. The results show significant differences from the laboratory calibration, good agreement with the calibrations based on two rocket-flights flown in 1997 and excellent stability of the CDS instrument during the same year. It is suggested that this method be used to monitor the in-flight calibration of future EUV spectrometers.

19.1 Introduction

Plasma parameters such as densities, temperatures and element abundances of the solar transition-region and corona can now be determined with a good accuracy, using extreme-ultraviolet (EUV) spectrometers such as CDS and SUMER on board SOHO. However, any uncertainty in the intensity calibration affects the determination of these parameters, particularly when the emission lines are not close in wavelength or are seen in different detectors. The intensity calibration of the instruments is, therefore, a fundamental requirement for any scientific use of EUV spectra.

The CDS instrument observes the solar corona with two spectrometers, the Normal Incidence Spectrometer (NIS) and the Grazing Incidence Spectrometer (GIS). A description of the complete CDS instrument can be found in *Harrison et al.* [1995]. The CDS instrument is particularly complex to calibrate: it covers a wide wavelength range (15 nm to 78 nm) with five detectors giving six wavebands with second-order lines identified in three of them. Ground measurements of the CDS calibration [*Lang et al.*, 2000] suffered various uncertainties or limitations, and methods to check the in-flight calibration were needed. *Del Zanna* [1999] and *Del Zanna et al.* [2001] presented a comprehensive study, providing the first complete in-flight inter-calibration of all nine CDS channels. The in-flight calibration has been achieved with the use of a calibration method which compares observations with the most up-to-date atomic data provided by the CHIANTI database: see *Dere et al.* [1997]. Excellent agreement was found with the results of the two independent calibrations based on rocket-borne instruments flown in 1997 [*Brekke et al.*, 2000; *Thomas et al.*, 1999], thus showing the validity of the method adopted. On the other hand, significant differences remained with some of the ground calibration results. In particular, the NIS-1 and all the GIS responsivities in first-order were found to be underestimated, in the ground calibration, by factors of about two. The cross-calibration of the CDS channels was found to be stable during 1997.

19.2 A Calibration Method Based on Atomic Data

In the absence of a suitable on board calibration source, the only possibility is to use the solar emission as a 'calibration' source. The calibration process consists of four steps. The first step is the selection of the most suitable set of observations where the effects of solar variability are negligible. This is extremely important for all cases of cross-calibration between channels that do not observe simultaneously, as is the case of the GI and NI spectrometers. Solar rotation, spatial overlapping and temporal variability, are all issues. In particular, the high variability in all the transition-region lines, predominantly located at the supergranular network boundaries, makes most non-simultaneous observations unusable. The second step is the direct cross-calibration between spectrally-overlapping regions, when they are present, as in the case of CDS.

The third step is the selection of the most suitable 'calibration' lines to be used. The idea is to choose only those groups of calibration lines whose ratios are independent of the observed source. The first ratios to examine are branching ratios (ratios of lines that share a common upper-level). These intensity-ratios depend only on the radiative transition probabilities, and are generally known with 10 % accuracy. Next, ratios of density-insensitive lines are considered, by comparing observed and calculated values. A differential emission measure (DEM) analysis must be performed to assess blending and to take into account any temperature effects in temperature-sensitive calibration line-ratios. It is important to check that each line ratio is indeed constant both temporally and spatially. This can be done by observing different regions on the Sun. Also, one must check if there are any opacity effects. The procedure is then to apply the comparison to all the available ions. When agreement is found between the results obtained by the use of many lines of different ions, the relative calibration between the various channels is obtained.

For each pair of lines of the same ion, the responsivity ratio was derived from the observed and theoretical radiance-ratio. For each ratio, once one responsivity value was fixed, then the other is obtained directly. Figure 19.1 shows the CDS absolute responsivities derived from various line-ratios by fixing the value of one reference line for each ion. The responsivities of the reference lines were chosen in order to fit a continuous, smooth curve for each channel. The uncertainties in the ratios have been calculated by taking the uncertainties in the line intensities and adding 10 % to account for unknown uncertainties of the calculated atomic physics values. These uncertainties, therefore, do not include all possible systematic errors and should be considered as lower estimates. However, the results obtained from different observations (superimposed on Figure 19.1) show a small scatter, well within the estimated uncertainties, which gives confidence in the results.

Note that if only density- and temperature-insensitive ratios are used, the results are independent of the adopted densities, the ionization equilibrium or the temperature distribution of the source. Also note that uncertainties in the atomic data are difficult to estimate, but typically are 10 % to 30 %. The key issue is to identify all the calibration ratios that have shown excellent agreement (say within 10 %) between previous solar observations and predictions based on atomic theory. There is no reason why the calibration ratios observed by different EUV instruments should differ, if the same atomic data are used and

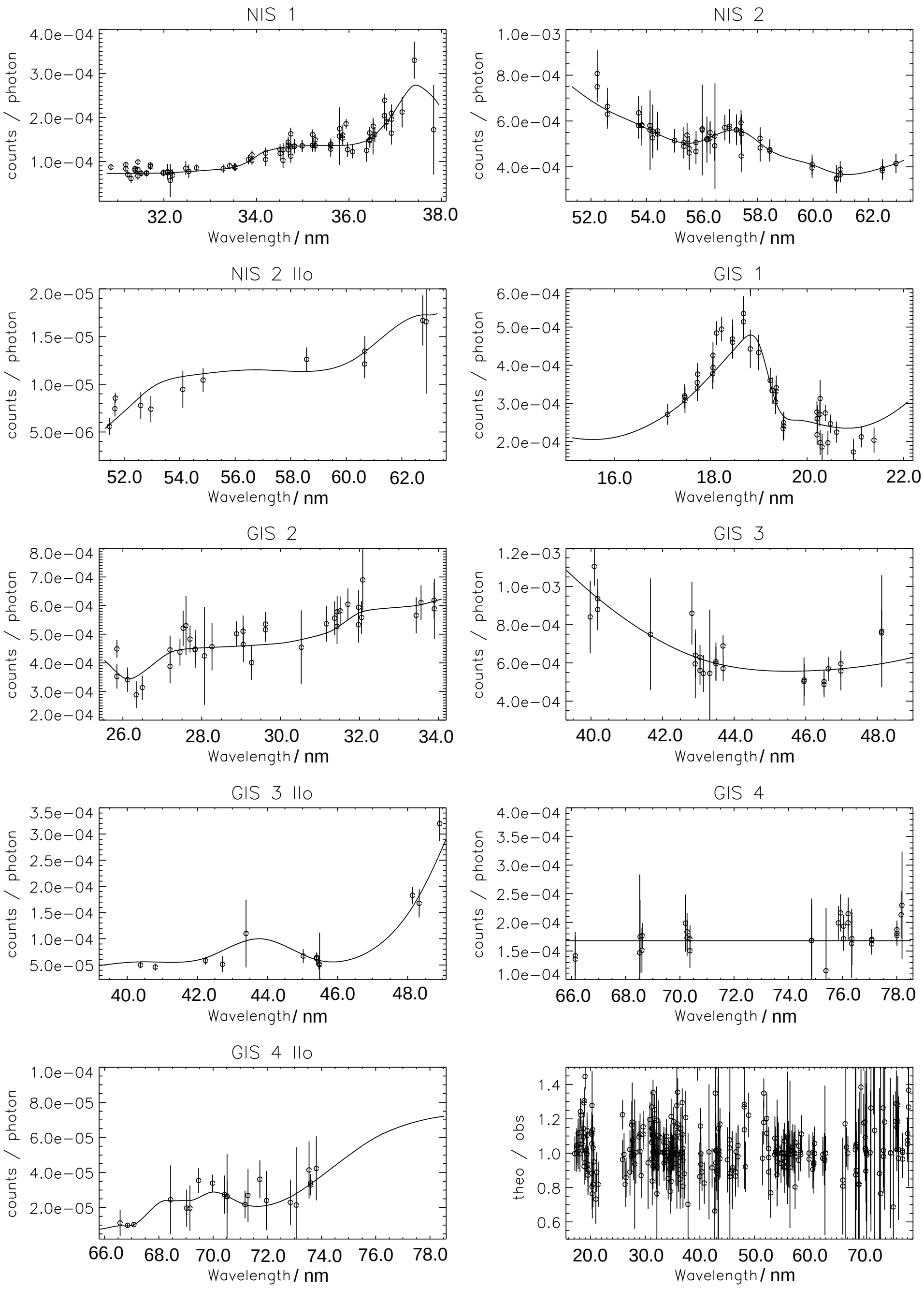

Figure 19.1: The CDS NIS and GIS responsivities (solid lines), first and second order, as derived from pre-loss-of-attitude observations. The responsivities derived from all the line-ratios used are superimposed. The bottom-right plot shows the ratio of the theoretical to the observed line-intensities for all the lines used.

the instruments are well-calibrated against primary standards.

This method has already been applied a few times in the past. *Neupert and Kastner* [1983] used this method for an in-flight calibration of the OSO V and OSO VII EUV spectrometers, in the 15 nm to 40 nm range. Recently, the method was successfully applied by *Brosius et al.* [1998a, b] to calibrate the Solar EUV Rocket Telescope and Spectrometer observations in 1995 (SERTS-95), using averaged active-region and quiet-Sun spectra and CHIANTI (version 1.01, except for Fe XIV). The same method was also applied by *Young et al.* [1998] to check the calibration of the SERTS-89 active-region spectrum [*Thomas and Neupert*, 1994].

In order to make full use of this diagnostic method for calibration purposes, given the uncertainties in the atomic data and the observed intensities, it is essential to use as many lines emitted by the same ion as possible. It is also important to use as many ions as possible, in order to reduce the possibility that incorrect atomic data for a single ion would affect the results.

The fourth step is to choose, for each calibration line, the most appropriate observations. This is not trivial. It is useful to observe different solar regions (e.g., on-disc and off-limb spectra, as well as quiet-Sun and active regions) in order to assess line identifications (in particular the absence of blending) and the constancy of the calibration ratios. Also, one should select observations where the plasma has uniform density and is isothermal. This reduces any effects that inhomogeneities can have on the line ratios and allows the use of lines that are not strictly temperature- and density-insensitive.

It is recommended that, in the absence of any more direct techniques, future EUV spectrometers observe a sufficient number of 'calibration' lines which can be used to constrain the relative calibration of the spectral region(s) observed. Possibly, these 'calibration' lines should be formed in the corona, rather than in the transition region.

19.3 The CDS In-flight Calibration

In the case of CDS, the intercalibration studies that have been routinely run since the beginning of the mission are not sufficient to obtain a comprehensive calibration of all the CDS channels, since they were designed for another purpose and only few spectral lines were observed. Moreover, only a few reliable calibration line-ratios are observed in each spectrometer. The worst case is represented by the NIS; there is no good line-ratio that can be used for an accurate cross-calibration between NIS-1 and NIS-2. The in-flight cross-calibration of the NIS channels, therefore, requires that NIS and GIS observations are considered together. *Del Zanna et al.* [2001] described the full-wavelength GIS and NIS near-simultaneous observing sequences that have been designed and performed for the purpose of monitoring the CDS in-flight responsivity.

A large number of line-ratios useful for the CDS calibration has been identified and described in *Del Zanna* [1999] and *Del Zanna et al.* [2001]. In most cases, agreement with previous findings based on CHIANTI predictions and SERTS observations [*Young et al.*, 1998; *Del Zanna*, 1999; *Brosius et al.*, 1998b] has been found, although many more cases have been highlighted. Only a few examples are given below.

Among the brightest lines in the CDS spectra are the doublets, whose radiance-ratio in the optically-thin, collisional case equals two. Unfortunately, in most cases the doublets, when observed by CDS, are blended with other lines. In the case of the Fe XVI (NIS-1, 33.54 nm and 36.0 nm lines), the line at 33.54 nm is blended, not only with a Mg VIII line, but also with an Fe XII [*Del Zanna*, 1999]. The Al XI, Ca X and Mg X doublets are also blended, but this time with transition-region lines. The doublets are free of blending only in off-limb spectra, where they become the strongest NIS-2 lines.

Transition-region (cool) lines are crucial for a relative calibration of the NIS-1 and NIS-2 channels. Most of the NIS-1 lines are coronal lines, but most of those observed by NIS-2 are formed in the transition region. So these two channels can only be cross-calibrated by use of GIS spectra, which record both transition-region and coronal lines.

The helium lines are a special case that deserves mention. Although the physics of the formation of the helium lines is still not understood [see, e.g., *Andretta and Jones*, 1997], the helium lines are extremely useful for calibration purposes. In fact, they are the brightest lines in the solar EUV spectrum, and their radiance ratios are exceptionally constant, independent of the part of the solar atmosphere observed. This remarkable (yet unexplained) characteristic of the helium lines is described in *Del Zanna et al.* [2001] but was already noted by *Andretta and Jones* [1997] using Skylab data [*Vernazza and Reeves*, 1978]: the lines of the He I series present constant radiance ratios against the 58.435 nm resonance line. The same applies to the ratio of the He I/He II resonance lines, which is also constant, independent of the solar region observed. For our use, the Skylab data of *Vernazza and Reeves* [1978] presented two serious problems. One problem was the low spectral resolution, which led to most of the helium lines being blended. Another problem was the uncertainty of the calibration, especially at shorter wavelengths, where the He II 30.378 nm resonance line is. Unfortunately, no accurate measurements of absolutely-calibrated He I and He II line intensities have been found in the literature, and the only set of well-calibrated values are indeed those reported in *Vernazza and Reeves* [1978], which in turn rely on a laboratory calibration and rocket flights. The CDS instrument, for the first time, overcomes these two problems. All the lines are well-separated. For example, the He II 30.378 nm line is well separated from the Si XI 30.33 nm resonance line. *Del Zanna* [1999] has analysed a large number of NIS-2 observations, and has confirmed that the He I line-ratios are indeed constant in the quiet Sun and coronal holes. The same applies to the He I/He II resonance-line ratio, with an average value measured by CDS of about 0.07. The CDS in-flight calibration found by *Del Zanna et al.* [2001] gives excellent agreement with the Skylab data for the He I 53.7/58.4 nm and He I/He II ratios, thus independently confirming the Skylab in-flight calibration. The results for the He I 53.7/58.4 nm ratio are also in excellent agreement with the rocket-flight results of *Brekke et al.* [2000], although not with the laboratory calibration.

19.4 Conclusions

I have reviewed some of the findings of *Del Zanna et al.* [2001] that can be of general use for the in-flight calibration of future EUV spectrometers such as those that will be flown on board Solar-B. Given the characteristics of the current EUV instruments, and the experience gained in the case of CDS, it is suggested that the calibration performed on the ground be reviewed and monitored with an in-flight calibration such as the one presented here. Long-term variations of the absolute calibration should still be checked against rocket flights which are calibrated on the ground against primary standards before and after the flight.

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