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Solar EUV/FUV Irradiance Variations: Analysis and Observational Strategy

Matthieu KRETZSCHMAR^{1,2}, Thierry DUDOK de WIT¹,
Jean LILENSTEN³, Jean-Francois HOCHEDÉZ², Jean ABOUDARHAM⁴,
Pierre-Olivier AMBLARD⁵, Frederic AUCHÈRE⁶, and Said MOUSSAOUI⁷

¹LPCE/CNRS, Orléans, France
e-mails: matthieu.kretzschmar@cnrs-orleans.fr (corresponding author),
ddwit@cnrs-orleans.fr

²SIDC, Royal Observatory of Belgium, Brussels, Belgium
e-mail: hochedez@oma.be

³LPG/CNRS, Bâtiment D de Physique, Saint-Martin d'Hères, France
e-mail: jean.lilensten@obs.ujf-grenoble.fr

⁴LESIA, Observatoire de Paris, Meudon, France
e-mail: jean.aboudarham@obspm.fr

⁵GIPSA-lab/Dept. Images and Signals- CNRS UMR5216, Grenoble, France
e-mail: bidou.amblard@lis.inpg.fr

⁶IAS, Université Paris-Sud, Orsay, France; e-mail: frederic.auchere@ias.u-psud.fr

⁷IRCCYN, Nantes, France; e-mail: said.moussaoui@irccyn.ec-nantes.fr

A b s t r a c t

The knowledge of solar extreme and far ultraviolet (EUV) irradiance variations is essential for the characterization of the Earth's upper atmosphere. For a long time, this knowledge has been based on empirical models, which are themselves based on proxies of the solar activity. However, the accurate modeling and prediction of the Earth's upper atmosphere necessitate to improve the precision on the irradiance and its variations below about 200 nm. Here, we present a review of recent works made by the authors that aim at quantifying the irradiance variability at these wavelengths, and that lead to new way of monitoring the solar EUV/FUV irradiance spectrum. In more details, it is shown that the

quantification of the high level of redundancy in the solar spectrum variability allows to envisage measuring only a small portion of the spectrum without losing essential knowledge. Finally, we discuss what should and could be measured in order to retrieve the solar extreme and far ultraviolet spectrum.

Key words: solar irradiance, EUV, FUV, space weather, aeronomy.

1. INTRODUCTION

The solar irradiance (or solar flux) in the extreme (EUV, from 10 to 121 nm) and far ultraviolet (FUV, from 122 to 200 nm) spectral ranges is of great importance for space weather. First, it is responsible for the ionization, dissociation, and heating of the upper terrestrial atmosphere. The specification of ionospheric quantities such as the Total Electron Content (TEC) heavily relies on it. Second, this part of the spectrum is highly variable on both long and short time scales. During intense solar flares, the flux may increase by more than an order of magnitude, especially shortward of 20 nm. These variations have important consequences on the ionosphere, but also on the lower atmospheric layers. For a recent review on the importance of the EUV flux for space weather, see Lilensten *et al.* (2007).

The solar EUV spectrum has been poorly observed in the past. In particular, there has been no continuous monitoring of the solar EUV irradiance between the end of measurements by Atmosphere Explorer E in 1981 and the launch of the NASA Thermosphere Ionosphere Mesosphere Energetics Dynamics (TIMED) spacecraft in January 2002 (see Woods *et al.* 2005) for details on EUV measurements history). To compensate for this lack of data, which has been termed the “EUV hole”, several models have been developed. These models compute the EUV irradiance in several spectral boxes that can be used directly in models of the Earth’s upper atmosphere. Most of these models, such as SERF1 (Hinteregger *et al.* 1981), EUVAC (Richards *et al.* 1994), and SOLAR2000 (Tobiska *et al.* 2000), are based on the use of solar activity proxies such as F10.7, the solar radio flux at 10.7 cm. Recently, new proxies have been introduced: E10.7, that represents the whole solar EUV flux scaled to F10.7, and E140, that is the flux integrated from 1 to 40 nm (Tobiska *et al.* 2000). The NRLEUV model (Warren *et al.* 2001) uses emission measure distributions and full-disk spatially-resolved solar images. These models have been – and still are – very useful, however space weather operations require an even more precise knowledge of the solar flux (Lathuillère *et al.* 2002), in particular for the Earth upper atmosphere modeling (Lilensten and Bornarel 2006). Woods *et al.* (2005) have shown that for a particular (but randomly chosen) day, the modeled EUV spectra can differ from the observed value by more than a factor 2 (for older reviews on the

comparison between models and observations, see also Lean 1990 and Tobiska 1993). What is urgently needed is not just spectral and temporal coverage but also radiometric accuracy.

The SEE (Solar Extreme-ultraviolet Experience) instrument onboard TIMED measures since early 2002 the solar spectrum from 26 to 193 nm, with a 0.4 nm resolution (Woods *et al.* 2005). The TIMED/SEE makes up to 15 measurements per day of the solar spectrum, averaged over 3 min each. This instrument offers an unique opportunity to improve our knowledge of the spectral variability and to investigate which parameters are important for retrieving the solar flux when no direct measurements exist. In this paper, we emphasize how the work that has been made recently by the authors to quantify the solar EUV/FUV irradiance variation can lead to new observational strategy. In Section 2, we present results on the quantification of the spectral variability redundancy and how it agrees with solar indices. Section 3 concentrates on the implications of these results for defining what should be measured and we explicitly propose sets of spectral lines that should be observed. Finally, we discuss our results and conclude in Section 4.

2. ANALYSIS OF THE SOLAR EUV SPECTRUM

The main mechanisms involved in the formation of the solar irradiance EUV spectrum under quiet conditions are understood (Lilensten *et al.* 2008). The spectrum consists of continuum emission that is mainly caused by composed of free-bound transitions (electronic recombination), and of spectral lines corresponding to atomic transitions of the ions that are present in the solar atmosphere.

Figure 1 shows three different solar spectra obtained under quiet conditions. The first one (black) is the spectrum integrated over the whole solar surface as measured by TIMED/SEE on March 16, 2007, when no sunspots were present. The second one (dotted) has been measured at very high spectral resolution on a quiet portion of the solar disk by the SUMER spectrometer (Curdt *et al.* 2001), and the third one (thick gray) has been modeled using atomic data and the average quiet Sun intensity of about 20 spectral lines (Kretzschmar *et al.* 2004). The last two intensity spectra have been converted into irradiance by multiplying by $\pi R_0^2/d_0^2$, where R_0 is the solar radius and d_0 is the Sun-Earth distance, and degraded to the spectral resolution of TIMED/SEE. As can be seen in the figure, the main features of the spectrum (i.e., the continuum and the spectral lines) agree between the different spectrums. The observed disagreement for the absolute value of the flux, mainly for the continuum above 90 nm and below 70 nm, can be explained in part by the different spectral resolution of the instrument and the integration over the solar disk. Other sources of error can come from the atomic physics and

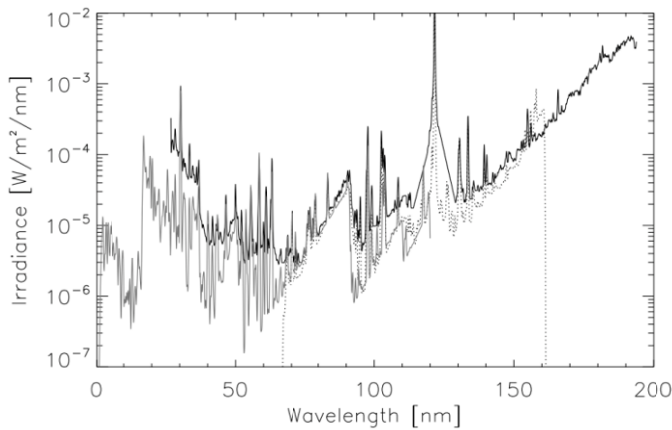


Fig. 1. Solar irradiance spectra for quiet conditions. The thick black curve corresponds to TIMED/SEE measurements for a quiet Sun, the dotted curve is from (Curd *et al.* 2001) and the thick gray curve is from (Kretschmar *et al.* 2004).

from the fact that the computation does not take easily into account the non-equilibrium conditions in the solar atmosphere (for example a non-Maxwellian distribution). A true inter-calibration study should be performed to go beyond these explanations but this is not the purpose of this paper.

For an operational space weather service, it is crucial to know the variation of the solar EUV spectrum with solar activity. To answer this question, one would ideally require continuous observations of the Sun over at least one solar cycle and monitoring of the FUV/EUV irradiance with a very good temporal and spectral coverage, as well as an excellent absolute calibration. This is not feasible, although the EVE instrumental suite (Woods *et al.* 2005) onboard the Solar Dynamics Observatory (to be launched in 2008) will significantly improve the monitoring of the EUV spectrum. TIMED/SEE, however, has now been monitoring the solar FUV/EUV irradiance for several years with up to 15 measurements per day. Enough data have been accumulated to answer the question in a statistical sense. This is the approach developed by Dudok de Wit *et al.* (2005), whose first objective was to quantify the remarkable degree of redundancy observed between the time evolutions of various EUV spectral lines. To do so, the spectral irradiance matrix $I(l, t)$, after proper normalisation, is decomposed into a set of separable functions of time t and wavelength l :

$$I(\lambda, t) = \sum_i c(\lambda, i) \times f(i, t).$$

This decomposition is unique and is done by Singular Value Decomposition (Golub and van Loan 1996). The $f(i, t)$ components describe the independent (actually orthonormal) temporal variations associated with the spectrum,

while $c(l, i)$ can be seen as the projection of $I(l, t)$ on the i th temporal component. The components $f(1, l), f(2, l), \dots$ are conventionally sorted in decreasing order of variance.

The first result of Dudok de Wit *et al.* (2005) is that over 95% of the variance of $I(l, t)$ can be described with two components only. This result indicates that the variation of the FUV/EUV irradiance is strongly redundant between different wavelengths. It also allows us to represent the similarities and differences in the irradiance variation in a very compact way. Since the two first components describe the salient features of the spectral variability, we can plot $c(2, l)$ versus $c(1, l)$; see Fig. 2. In this two-dimensional map, each point corresponds to a wavelength. The distance between each pair of wavelengths reflects their degree of similarity: the closer the two points are, the more similar the irradiance variations at these wavelengths.

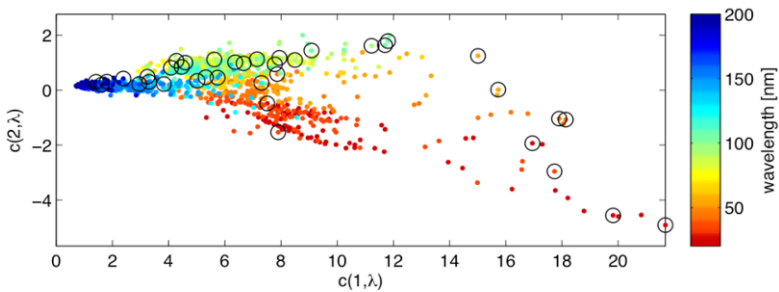


Fig. 2. 2D representation of spectral similarities in FUV/EUV irradiance variations. Each point is colour coded by its corresponding wavelength. The 38 strongest spectral lines are circled. The meaning of the axes is discussed in Dudok de Wit *et al.* (2007); what matters here is the relative distance between the points. Plot based on TIMED/SEE level 2 data between Feb. 25, 2002 and May 1, 2007. Colour version of this figure is available in electronic edition only.

As expected, long wavelengths are tightly grouped together and short wavelengths are located far from long ones. The dispersion of very short wavelengths reflects the marked differences between emissions originating from the hot corona. Some wavelengths stand out of the cluster of points; this is notably the case for the hydrogen and helium lines, which exhibit a relatively singular behavior.

More recently, Dudok de Wit *et al.* (2008) have used the same representation to determine how well the different solar activity proxies can reproduce the spectral variability. For that purpose, they could not distinguish a particular index (excluding instrumental constraints) apart from the sunspot number, which is very isolated in the 2D-representation and presents the greatest dissimilarity. Their results show that no single index can successful-

ly describe both the level of variability on different time scales. The Mg II and the CaK indices can describe properly the long-term (> 27 days) evolution of the least-energetic part of the EUV spectrum but cannot model the short-term evolution. Conversely, the Mg II, CaK and He I indices are found to be representative of the short-term evolution of coronal lines. Finally, the inspection of the connectivity map obtained with two different normalizations indicates that no combination of indices could reproduce the variability of the EUV spectrum. Why not, then, try to reconstruct the EUV irradiance from a linear combination of a few spectral lines (or spectral bands) that are monitored with a dedicated instrument?

3. OBSERVATIONAL STRATEGY

The results obtained so far support the idea that from a small number of properly chosen wavelengths, one could reconstruct the whole EUV/FUV spectrum with a precision that meets the requirements of a space weather service. This idea has been investigated in two complementary approaches.

The first approach is physics-based. Kretzschmar *et al.* (2006) selected intense spectral lines from the SEE spectra, with the constraint that (1) these lines must cover the range of temperatures found in the solar atmosphere, and (2) they can be assumed to be optically thin. They then computed the whole Sun differential emission measure (DEM) for each observing day, which allowed in turn to compute the non-observed part of the spectrum (i.e., all optically thin spectral lines to the exception of the extracted ones) for that day. The optically thick part of the spectrum was deduced empirically (i.e., through least square fitting) from one observation. Based on this, they determined six spectral lines from which the whole spectrum could be computed for each observation. Relative temporal variations were well reproduced in this study and a good general agreement has been found between the absolute value of the computed and observed spectra, especially for spectral lines (basically within 15%). The disagreement between observed and modeled spectrum in this study can be due to the failure of one or several assumptions made to use the DEM formalism (e.g., constant abundance), errors in atomic data, non-inclusion of weak spectral lines that contribute to the continuum, and non-proportionality between the various optically thick parts of the spectrum.

The second approach is statistical, based on the decomposition presented in Section 2. Dudok de Wit *et al.* (2005) built a dendrogram of the 38 most intense spectral lines measured by TIMED/SEE, see Fig. 3. In such a plot, redundant lines with very similar dynamics are linked by a short branch. Dendrograms therefore provide a simple strategy for selecting spectral lines that describe the different facets of the spectral variability. From this, the au-

thors extracted a first set of 14 lines, from which a smaller subset of 6 lines was found to minimise the error on the reconstructed spectrum. The 14 lines are listed in Table 1. Interestingly, the best candidates for spectral reconstruction are almost the same as those selected by Kretzschmar *et al.* (2006).

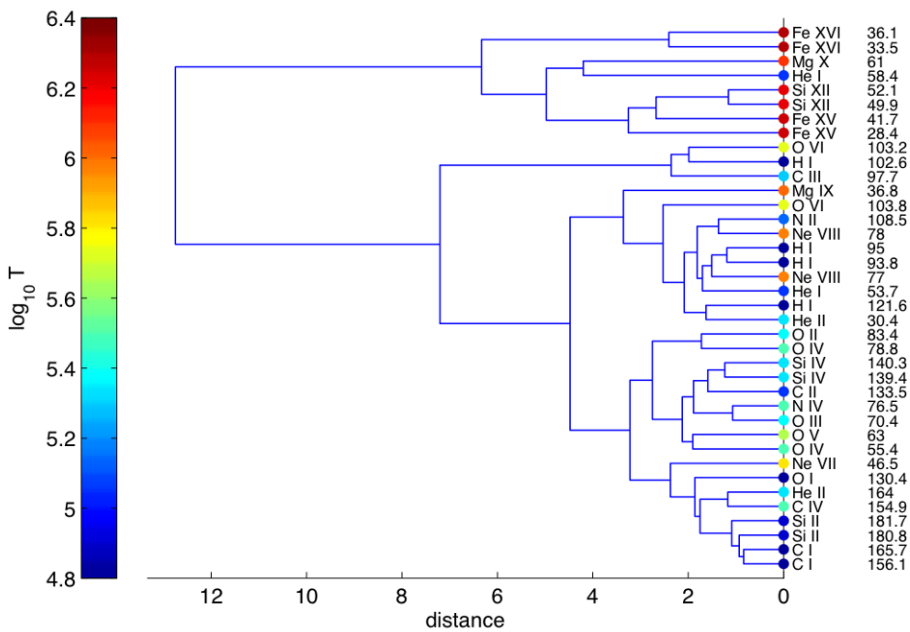


Fig. 3. Dendrogram of the strongest 38 EUV lines. The horizontal distance between each pair of lines reflects their degree of similarity. The colour code gives the characteristic emission temperature of each line. See Dudok de Wit *et al.* (2005) for a detailed explanation. Colour version of this figure is available in electronic edition only.

Table 1

Set of 14 lines that are appropriate for reconstructing the salient features of the solar EUV/FUV spectrum. From this, a subset of typically 6 non-redundant lines must be chosen.

He II	30.38 nm	Mg X	60.98 nm	O I	130.43 nm
Fe XVI	33.54 nm	O III	70.38 nm	C II	133.51 nm
Fe XV	41.73 nm	O II	83.42 nm	C IV	154.95 nm
Ne VII	46.52 nm	C III	97.70 nm	Si II	181.69 nm
O IV	55.43 nm	H I	121.57 nm		

4. DISCUSSION AND CONCLUSIONS

Ionospheric specification models require increasingly accurate measurements of the solar EUV/FUV spectrum, for which currently available proxies are of limited use. By using both a physics-based and a statistical approach, we have shown that the variability of the EUV/FUV spectrum exhibits a strong degree of redundancy, 2 dimensions being able to capture more than 95% of the variance. This leads us to advocate a different strategy, in which the EUV/FUV spectrum and its variability are reconstructed from the measurement of a few (typically 6) carefully chosen spectral lines or spectral bands. The choice of the best set of lines is application dependent. Lilensten *et al.* (2007) describe a methodology for determining the lines that are most appropriate for ionospheric specification. A solar physicist may want to use a different set, to optimize for example the information on the solar atmosphere contained in the spectrum.

There is also a strong instrumental motivation for reconstructing the spectrum from a few lines only. Spectrographs are costly and, like all EUV/FUV instruments, suffer from ageing. One could use instead arrays of photodiodes, for which more robust technologies are being developed. The LYRA radiometer (Hochedez *et al.* 2006) onboard the PROBA2 satellite (due for launch in 2009), will provide the first experimental ground to our approach as it will cover 4 bands: 1-20 nm, 17-70 nm, 115-125 nm and 200-220 nm. In Fig. 4, we give an example of how the response of diodes with different types of metallic filters compares against the various wavelengths between 26 and 193 nm, using the same representation as in Fig. 2. One can readily check that the diodes with Au, Pd, Ag and Cu filters are redundant, as are the diodes with Al and Si filters.

Several aspects still need to be investigated for enhancing further the accuracy and the precision of the solar spectrum reconstruction. For example, we might advantageously use time-series that are not made only of spectral

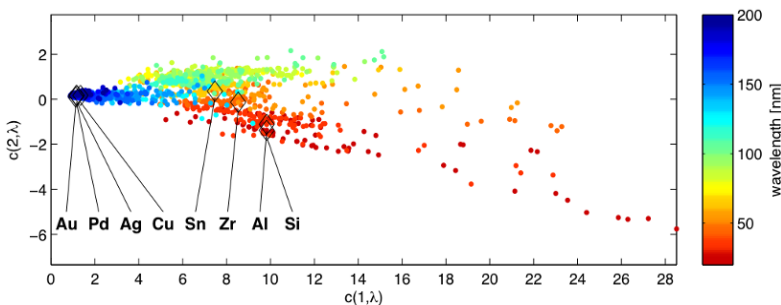


Fig. 4. Location of diodes with various spectral bands (given by their multilayer metal filter name), using the same representation as in Fig. 2. Colour version of this figure is available in electronic edition only.

FUV/EUV irradiance. For example, we may think of gross estimates of the disc proportion covered by Active regions and by Quiet Sun, which should allow higher precisions for mid-term reconstruction. This is one of the reasons why the second generation of LYRA radiometers could include EUV imaging channels at relatively low spatial resolution. Multi-layers would permit a twofold benefit on top of their being focusing mirrors. First, they can pave the EUV spectrum with overlapping passbands, or alternatively sample the most linearly independent wavelength ranges. Second, they can act as photocathodes, delivering a signal that could serve to correct for long-term drifts in the performance.

The impact of flares on the spectral reconstruction must be taken into account; the method could then be implemented for several temporal scales in order to account for the difference in the physics controlling short-term brightenings (flares) and the longer terms (rotation, solar cycle). Another important point is the spectral variability below 26 nm, for which we must wait for SDO/EVE to cover that range with a good spectral resolution. The spectral variability above 193 nm is relatively easier to reconstruct. Work on this is in progress, using data from spacecraft such as UARS/SUSIM.

The authors of this paper intend to continue their efforts in this direction.

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