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Review on the solar spectral variability in the EUV for space weather purposes

J. Lilensten[1], T. Dudok de Wit[2], M. Kretzschmar[3], P.-O. Amblard[4], S. Moussaoui[5], J. Aboudarham[6], and F. Auchère[7]

[1]LPG, CNRS and Joseph Fourier University, Bâtiment D de Physique, BP 53, 38041 Saint-Martin d'Hères cedex 9, France
[2]LPCE, CNRS and University of Orléans, 3A avenue de la Recherche Scientifique, 45071 Orléans cedex 2, France
[3]SIDC, Royal Observattory of Belgium, avenue circulaire 3, 1180 Brussels, Belgium
[4]GIPSAlab, CNRS, 961 Rue de la Houille Blanche, BP 46, 38402 St. Martin d'Hères cedex, France
[5]IRCCYN, 1, rue de la Noë, BP 92101, 44321 NANTES Cedex 3, France
[6]LESIA, Paris Observatory, 5 Place Jules Janssen, 92195 Meudon, France
[7]IAS, CNRS and Paris-Sud University, Bâtiment 121, 92405 Orsay cedex, France

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Abstract. The solar XUV-EUV flux is the main energy source in the terrestrial diurnal thermosphere: it produces ionization, dissociation, excitation and heating. Accurate knowledge of this flux is of prime importance for space weather. We first list the space weather applications that require nowcasting and forecasting of the solar XUV-EUV flux. We then review present models and discuss how they account for the variability of the solar spectrum. We show why the measurement of the full spectrum is difficult, and why it is illusory to retrieve it from its atmospheric effects. We then address the problem of determining a set of observations that are adapted for space weather purposes, in the frame of ionospheric studies. Finally, we review the existing and future space experiments that are devoted to the observation of the solar XUV-EUV spectrum.

Keywords. Ionosphere (Modeling and forecasting; Solar radiation and cosmic ray effects) – Solar physics, astrophysics,and astronomy (Ultraviolet emissions)

1 Importance of the XUV-EUV solar flux for space weather applications

The solar irradiance in the ultraviolet range is one of the key parameters for space weather (Lathuillère et al., 2002) and yet very few continuous and spectrally resolved measurements exist. The irradiance must be measured from space but present detectors suffer from degradation, which prohibits long-term measurements. Several types of models have been developed with the aim of bridging the resulting lack of observational data. Before we detail the impact of the solar irradiance on geospace, it is important to specify what we mean by Extreme UltraViolet (EUV) and Soft X-ray (XUV). Different acronyms are used in the literature for describing electromagnetic radiations. A physicist and a physician may well speak of the same radiation without understanding each other; this is why recent studies have been carried out with the aim of standardizing the denominations (it is of course totally out of the question to normalize the solar flux itself). An ISO norm has recently been proposed and is now officially listed as Final Draft International Standard (Tobiska and Nusinov, 2006). The denominations for the different parts of the spectrum are tabulated in Table 1. The wavelengths we shall focus on range from 0.1 nm to 10 nm (XUV) and from 10 nm to 121 nm (EUV). We will also briefly consider the UV range, including the strong Lyman-α line at 121.5 nm.

Our rationale is the impact of these wavelengths on the upper atmosphere. The solar irradiance in the XUV-EUV range is mostly absorbed by molecular oxygen, atomic oxygen, and molecular nitrogen. The main processes at work are ionisation, excitation, and dissociation. Photoionisation is mostly efficient above 150 km, and filters the light down to about 80 km. The main species involved are O_2, N_2 and O. Between 70 and 280 nm, molecular photodissociation becomes an important or predominant process; it filters the light down to low altitudes, typically 20 km. Note that the near ultraviolet (300 to 400 nm) is mostly absorbed by the dissociation of ozone, whose efficiency peaks around 40 km, i.e. far below the altitudes of concern in this review paper.

The physics of absorption processes in the upper atmosphere was first described by Chapman (1931a,b, 1953). Most recent studies still rely on his early work. A full

Correspondence to: J. Lilensten
(jean.lilensten@obs.ujf-grenoble.fr)

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Table 1. Irradiance ranges with corresponding energies and temperatures in the case of thermodynamic equilibrium. Note that the irradiances are defined by their wavelength and not by their energy range.
(1) Range adopted by the World Health Organisation and the International Commission on Illumination.
(2) Definition adopted in the aeronomy community. Other communities may consider 10 nm instead of 30 nm, and 100 nm instead of 120 nm. See also the ISO norm project by Tobiska and Nusinov (2006).

Domain	Subdomain	Acronym	Wavelength range $\Delta\lambda$ [nm]	Energy $\frac{hc}{\lambda}$ [eV]	Temperature [MK]
Ultraviolet		UV	100–400	3.1–12.4	0.072–0.29
Ultraviolet	A(1)	UVA	315–400	3.1–3.9	0.072–0.090
Ultraviolet	B(1)	UVB	280–315	3.9–4.4	0.090–0.10
Ultraviolet	C(1)	UVC	100–280	4.4–12.4	0.10–0.29
Ultraviolet	Near	NUV	300–400	3.1–4.1	0.072–0.096
Ultraviolet	Middle	MUV	200–300	4.1–6.2	0.096–0.14
Ultraviolet	Far(2)	FUV	122–200	6.2–10.16	0.14–0.24
Ultraviolet	Lyman α		121–122	10.16–10.25	0.236–0.238
Ultraviolet	Vacuum	VUV	10–200	6.2–124	0.14–2.9
Ultraviolet	Extreme	EUV	10–121	10.25–124	0.24–2.9
X-ray			0.005–30	41.3–2.5×10^5	0.96–5.7
X-ray	Soft X-rays	XUV	0.1–10	124–1.24×10^4	2.9–290
X-ray	Hard X-rays		0.001–0.1	1.24×10^4–1.24×10^6	280–28 000
γ rays			<0.001	$>1.24\times10^6$	>28 000

description of the physics may be found in Lilensten (1999) and in Schunk and Nagy (2004). The impact of the XUV-EUV fluxes on space weather through the atmospheric system are important. Let us mention the three principal ones.

1.1 Satellite drag: a thermospheric process

One of the prime motivations for nowcasting and forecasting the solar XUV-EUV flux is the specification of atmospheric densities for spacecraft orbit determination, attitude control, and also for debris mitigation. When an object (spacecraft, or debris) travels through an atmosphere, it experiences a drag force opposite to the direction of its motion. As a first approximation, this drag force depends on the thermospheric density, the satellite velocity, the satellite cross-sectional area and a drag coefficient. The evaluation of the drag force is conditioned by the knowledge of the thermospheric density, which usually comes out of a model. The sources of density variations in the thermosphere are primarily the XUV and EUV fluxes, particle precipitation and electric fields. The physical processes involve photo-absorption, particle collisions, Joule heating and frictional heating. For space weather, the main consequence (amongst other phenomena) is a dilatation of the thermosphere. During periods of strong solar activity, the density may increase by a factor of 10 at the altitude of the International Space Station (400 km).

The prime goal of satellite operators is to predict the position of a space object with a accuracy of at least 20 km after 24 h. This prediction requires a permanent monitoring and adjustment of the drag equation through neutral atmosphere models. Several methods are currently used: the proxy approach, which relies on indices, today still remains important and is difficult to bypass for long-term studies. A technological approach consists of estimating the thermospheric drag using a reference object, such as a spacecraft with a well-determined cross section (Marcos et al., reported in Nicholas et al., 2000). Physical approaches consist in feeding the models with observations. These observations can, for example, be the UV airglow (Nicholas et al., 2000), the thermospheric temperature (Lathuillère et al., 2002), or ionospheric parameters, such as the Total Electron Content (TEC) (Lilensten and Blelly, 2002).

1.2 Telecommunication and positioning: ionospheric processes

The ionosphere influences electromagnetic wave propagation mainly through scattering, absorption and Faraday rotation (Leroy, 2000). The optical index depends strongly on the electron density and on the thermospheric composition which, like in the thermosphere, depend on the XUV and EUV fluxes, on particle precipitation, and on electric fields. An additional source is the physical link with the exosphere, in particular with the protonosphere. The underlying physical processes differ slightly from those encountered in the thermosphere, as they involve photo-ionisation, particle collision ionisation, currents and frictional heating. These processes produce (amongst other effects) rapid variations and generate small-scale disturbances, such as blobs, patches, and scintillations.

All existing models (physical, profilers, TEC derived from GPS, ...) fail in reproducing the real-time ionosphere, especially at high latitude and during solar events (Jakowski et al., 1999; Lunt et al., 1999; Lilensten et al., 2005). As for the thermosphere, there is a strong need for a permanent monitoring and adjustment of the equations and the strategy consists of using proxies or physical approaches (for example, with topside sounders). The ionosphere, however, is somewhat more easily accessible from the ground than from the thermosphere, thereby offering additional opportunities for calibrating models.

1.3 Space weather versus classical weather

Classical weather is somehow out of the scope of this review, and yet we mention it here since the different layers of the terrestrial atmosphere are intimately coupled. Several phenomena contribute to these changes; see, for example, the reviews by Haigh (2005), Bard and Frank (2006), and Calisesi et al. (2006). Some of these processes may be related to space weather. The principal ones are:

- Influence of the total solar irradiance. Records show such an influence over different time scales (Haigh and Blackburn, 2006). The influence of the total solar irradiance on time scales of decades or less is not as clear as for long-term effects. Typical estimates range from 6% to 30%, with a likely value of about 12% (Alley et al., 2007), which is below the value published 5 years earlier by the Intergovernmental Panel on Climate Change.

- Influence of the cosmic rays on condensation nuclei and thereby on cloud cover (Svensmark and Friis-Christensen, 1997; Svensmark, 2007). The microphysics is described in Harrison and Carslaw (2003). The impact on climate remains controversial as subsequent studies have failed to confirm a relationship (Laut, 2003; Damon and Laut, 2004).

- Indirect influence of the UV variability: above 30 km, the ozone response is well pronounced (Rozanov et al., 2005; Calisesi and Matthes, 2006). This, in turn, influences the dynamic coupling between the stratosphere and troposphere (Haigh and Blackburn, 2006).

- Influence of the solar wind: some mechanisms have been suggested as early as 1994 (Tinsley, 1994). In particular, Joule heating induced by the solar wind and interplanetary magnetic field may influence the circulation and ozone concentration in the middle atmosphere (Zubov et al., 2005).

- Impact of greenhouse gases, with, for example, the falling sky theory (Roble and Dickinson, 1989).

- Impact of upper lightning (Sentman et al., 1995) with red sprites, blue jets, elves, etc.

At least the two last ones may be directly related to the thermospheric and ionospheric processes.

Let us finally mention the importance of XUV-EUV irradiance measurements for modelling radiative transfers in planetary atmospheres, for simulating solar cell power and material degradation. Scientific applications of ultraviolet measurements to bodies other than the Sun have recently been reviewed by Brosch et al. (2005).

2 Origin and variations of the XUV-EUV fluxes

The Sun varies on all scales and the variability is strongly dependent on the wavelength. For some reviews, see the works by Lean (1987, 1991), Tobiska (1993), Pap et al. (1994) and Woods et al. (2005). Let us briefly examine the various solar origins of this XUV-EUV flux. The UV emission is generated at relatively low temperatures, i.e. in the chromosphere and in the transition region. At the lowest considered temperatures, there is no local thermodynamic equilibrium in the solar atmosphere. The source function can no longer be considered to be a Plank function, and must be evaluated instead by considering each individual atomic process that is involved in the generation of the spectrum. In other words, Table 1 cannot be used to infer the temperature of the formation of a line from its wavelength.

2.1 Near UV emission processes: electronic transition

Although the near UV has little impact on space weather applications, some UV lines are used as proxies for assessing the variability of the long wavelength range of the EUV spectrum. In the near UV range, one finds some distinct lines such as: H(δ) at 410.2 nm, Ca+ (line H) at 396.8 nm, Ca+ (line K) at 393.4 nm, Fe (line M) at 373.5 nm, Mg at 285.2 nm, Mg+ (line h) at 280.2 nm, and Mg+ (line k) at 279.5 nm. All these lines have a chromospheric or photospheric origin. They are very sensitive to solar activity. All of them are optically thick and the first phenomenon at work is collisions. In the UV range, one finds the hydrogen Lyman series, which includes the Lyα line at 121.5 nm, Lyβ at 102.5 nm, and Lyγ at 97.2 nm. These lines are typical electronic lines, in which the electron goes from a ground state (n=1) to higher states. Lyα corresponds to the n=1 toward the n=2 transition, Lyβ from n=1 to n=3, and Lyγ from n=1 to n=4. The energy gained through collisions or photon absorption may exceed the ionization threshold. This is the case in the chromosphere for Ca. However, at such temperatures, calcium atoms are almost all in the singly ionized state Ca II, with the single outer electron in a 4 s orbit (H line). The 4p orbit may eventually also be reached (K line). Ca II lines are collisionally controlled. These lines are also very sensitive to solar activity and are observable from the ground. Daily observations are performed at several observatories, in particular at Meudon and at Big Bear observatory (Johannesson et al., 1995).

Two other Fraunhofer lines in the near UV are important. Both are due to singly ionized magnesium, at wavelengths of 280.2 nm (Mg II h line) and 279.5 nm (Mg II k line). The electron transitions involved are similar to those for the Ca II H and K lines, and they are also collisionally controlled. These lines are widely used today as a solar activity index (Heath and Schlesinger, 1986). The core of the Mg II line is imprinted by the variability of the UV as it originates in the upper chromosphere, as compared to the wings, which are generated in the photosphere and are therefore insensitive to solar UV variations. The MgII index is calculated by taking the ratio of the irradiance at the core of the Mg II absorption feature at 280 nm to the average irradiance in the wings of the Mg II feature at approximately 276 and 283 nm. Because of that, the MgII index is a dimensionless quantity which is unaffected by most undesirable effects, such temporal and spectral changes in the instrument response (Viereck et al., 2001). This index is today derived from various instruments that differ in resolution, wavelength selection, and derivation method and yet are in excellent agreement (Cebula and Deland, 1998; de Toma et al., 1997; White et al., 1998).

Finally, the He II line at 30.4 nm is currently observed by the SEM (Judge et al., 1998) and EIT (Delaboudiniere et al., 1995) instruments on board SOHO, albeit with a resolution of a few nm. This spectral band is dominated by chromospheric emissions emitted around 50 000 K. All these quantities are strongly correlated both with each other, and with other proxies for solar activity, such as the $f_{10.7}$ decimetric index, thereby expressing the strong connections between different solar atmospheric layers (Floyd et al., 2005).

2.2 UV to XUV emission processes: line emission, free-free and free-bound processes

UV and EUV emission processes do not involve neutral atoms or singly charged ions, but multiple charged ions. The collision with an electron generates additional ionizations if the energy of the incident electron exceeds a threshold (typically 12 eV). We then have an ionization ($X^{+m}+e^{-}\rightarrow X^{+m+1}+2e^{-}$), in which the ion is left in an excited state, and goes to a state of lower energy by emitting a photon. We can also have radiative recombination ($X^{+m}+e^{-}\rightarrow X^{+m-1}$) with the emission of a photon. The impact with an electron may also leave the ion in an excited state such that it auto-ionizes after a short period of time ($X^{+m*}\rightarrow X^{+m+1}+e^{-}$). This excitation can be an electronic recombination ($X^{+m}+e^{-}\rightarrow X^{+m-1*}$), where a free electron is captured by the atom. After auto-ionization, the ion is mostly left in a ground state. Some of these processes can also occur with proton collisions or with photoabsorption. These processes, however, have a minor influence. Finally, charge transfer with the abundant hydrogen may leave the ion in an excited state, from which a photon is emitted ($X^{+m}+H\rightarrow X^{+m-1*}+H^{+}$).

Radiative recombination involves the transfer of a free electron to a captured electron (free-bound process). In the free-free case (or "Bremsstrahlung"), an electron is accelerated or decelerated through the interaction with a Coulombian potential of an ion. These two last processes are responsible for the continuum, in which all frequencies are excited, creating a continuous baseline in the solar spectrum. The other origin of the continuum is the recombination of electrons with bare carbon and oxygen nuclei. The physics involved depends on many parameters, such as the relative abundance of each element, the ionisation ratio, and excitation ratio (Arnaud and Rothenflug, 1985; Arnaud and Raymond, 1992).

On top of the continuum, several lines are worth examining. In the X-ray range, two resonance lines in the Fe XIV spectrum at 5.90 and 5.96 nm are emitted from the 3p ground state to the 4d state. Above active regions, the temperature of the lower corona can increase to about 4×10^{6} K. This results in the additional ionization of iron, especially Fe XV and Fe XVII, whose bright emissions motivated the choice of the 28.4 nm band for one of the filters of EIT on board SOHO (Delaboudiniere et al., 1995).

In the XUV range, resonance lines of helium-like ions of light elements arise, such as carbon (C V) at 4.03 nm, oxygen (O VII) at 2.16 nm and neon (Ne IX) at 1.345 nm. Similarly, there are lines of hydrogen-like ions, equivalent to the Lyman lines of hydrogen itself at UV wavelengths: the Lyα lines of hydrogen-like carbon (C VI) at 3.37 nm and oxygen (O VIII) at 1.90 nm.

In the EUV range, several intense lines are due to lithium-like ions. Lithium has three electrons, with the outer in the n=2 orbit. Excitation may take it from a 2-s sub-orbit to a 2p, and de-excitation back to 2 s results in two closely spaced lines forming a doublet. The lithium-like carbon (C IV) doublet at 155 nm is emitted at transition region temperatures. The lithium-like oxygen (O VI) doublet is at 103.2 nm and 103.8 nm, and originates in the coronal region. The lithium-like magnesium (Mg X) is at 61.0 nm and 62.5 nm, and the silicon (Si XII) is at 49.9 nm and 52.1 nm. Fe IX/X at 17.1 nm, which is also observed by EIT, is due to a 3p–3d transition.

2.3 The XUV-EUV-UV spectral variability

The variability of the solar irradiance over one solar cycle is very small in the visible range (less than 0.1%), and slightly larger in the infrared part (less than 1%). These numbers strongly increase shortward of 200 nm, where the variability may exceed 100% (Woods et al., 1998). The contribution of XUV-EUV to the total solar irradiance is very small, so that the variability of the latter remains comparable to that of the visible domain (Pap and Fröhlich, 1999). Some typical values of the variability are listed in Table 2. For a review on

Table 2. Long-term variability (in %) of some spectral lines and EUV/UV indices. The values represent the amplitude of the 11-year cycle normalised to the time average. The total solar irradiance is from SOHO/VIRGO, spectral lines are from TIMED/SEE, and the soft X-ray measurements from GOES/SEM.

total solar irradiance	Mg II index	Ca K index	Lyα 121.5 nm	He II 30.4 nm	Fe XV 28.4 nm	soft X-ray 0.1-0.8 nm	$f_{10.7}$ index
0.06	4	6	27	25	53	>200	77

the XUV-EUV variability, see Lean (1987) and Woods and Eparvier (2006).

The XUV-EUV variability has two components. The short-term and most variable component is associated with sporadic explosive events, such as bright points, flares, and eruptions. The EUV flux is enhanced by these eruptive events because of the temperature increase and electron acceleration. Free-free processes are enhanced, and the emission may increase by orders of magnitude (Phillips, 1995), especially in the XUV range (Woods et al., 2005). The second and slow variability component evolves on times scales of days to years and depends on full disc activity.

3 Are existing XUV-EUV models suitable for space weather?

There are several categories of aeronomical models. The first one consists of models that were first developed in the eighties and that rely heavily on data from Atmospheric Explorer mission (Hinteregger et al., 1973). Many models today still use the binning of the spectrum that was first proposed by Torr and Torr (1979). The success of this approach has to do with its simplicity and the existence of a set of absorption cross sections for each wavelength bin. There are two reference fluxes: one for active and one for quiet conditions. Other levels of activity are modelled by interpolating the decimetric index $f_{10.7}$. In the mean time, the experimental data used to determine the flux has gradually improved (Hinteregger, 1981; Hinteregger and Katsura, 1981; Torr and Torr, 1985).

Tobiska (1991) and Tobiska and Eparvier (1998) developed a different model, called EUV, using a more extended database. In comparison to the previous ones, this model retrieves the solar flux from the decimetric index and its average. The latest versions use new input parameters computed from a previous version of the code (Tobiska et al., 2000). EUVAC (Richards et al., 1994) is based on a reference flux that differs from the one used by Torr and Hinteregger, and relies on specific interpolation formula. EUVAC also adds physical constraints on the coronal flux. Its latest version, named HEUVAC (Richards et al., 2006), extends the EUV model below 5 nm and includes data from the SEE instrument on board TIMED (Woods et al., 2005).

All these models are valuable tools for aeronomic studies. None of them, however, can properly track solar activity. There are several reasons for this. The first one is the lack of data as the observations span at best 2 solar cycles. Secondly, because the observations are discontinuous in time, not all geophysical conditions are properly covered. Third, due to historical reasons, the wavelength resolution is rather coarse, with generally 39 bins. Finally, all these models rely on one or a few indices that only partly describe the multiple facets of solar activity. As shown by Dudok de Wit et al. (2007), none of the indices is representative of the variability of the EUV spectrum at all wavelengths. Therefore, accurate forecasting cannot fully rely on any of these models, regardless of their (numerous) qualities.

The second category of models uses additional inputs to reach better accuracy. The Flare Irradiance Spectral Model (FISM) is based on data from TIMED. FISM is an empirical model that estimates the solar irradiance from 0.1 to 190 nm with a 1-nm resolution, and with a time cadence of 60 s (Chamberlin et al., 2006). FISM can therefore model both eruptive events (for which very few accurate measurements exist) and long-term effects. Its inputs are traditional proxies (Mg II, $f_{10.7}$, and Lyα) and the irradiance in several bands (0–4 nm, 30.5 nm, 36.5 nm) to model the daily component. FISM also makes use of soft X-ray measurements from GOES (0.1–0.8 nm) to model flares. This model is the first one that can be used for near real-time space weather operations.

The third category involves a radically different approach that has been investigated independently by two teams. Instead of relying on existing irradiance observations, the idea is to use Differential Emission Measure (DEM) distributions derived from spatially and spectrally resolved solar observations, full-disk solar images, and a database of atomic physics parameters, to calculate the solar EUV irradiance (Kretzschmar et al., 2006; Warren, 2006). These efforts have resulted in the definition of a quiet Sun reference spectrum and solar minimum irradiance observations (Warren et al., 1998; Kretzschmar et al., 2004). NRLEUV2 is the latest model developed by Warren (2006), which also includes data from the CDS and SUMER spectrometers on SOHO. Although the overall agreement with the observations is quite good, some discrepancies subsist (Woods et al., 2005). The computed spectra overestimate the EUV continuum and cannot properly reproduce the observed irradiances below 160 nm. Such discrepancies are inevitable as the underlying conditions are not all fulfilled: not all lines are optically thin, assumptions need to be made on the pressure, temperature and electron density profiles, relative abundances must be known, etc. (Kretzschmar et al., 2004). In spite of these limitations, models such as NRLEUV2 are valuable tools for research. Their relevance for space weather operations is as yet more questionable.

4 Trying to retrieve the XUV-EUV fluxes from their effects is illusory

Since the impact of the XUV-EUV solar flux on the ionosphere is well understood, it is tempting to infer this flux from its effects. The reconstruction of the total solar irradiance from atmospheric effects has recently been reviewed by Krivova and Solanki (2005). Our interest is in the connection between the solar EUV-XUV flux and the thermosphere-ionosphere system. The variation of ionospheric parameters, such as the electron density profile as measured at one location by incoherent scatter radar, has been discussed by Mikhailov and Schlegel (2000) and Zhang et al. (2002). To extend this approach to a larger area, one may consider the critical frequency in the E region (Nusinov, 2006). Thermospheric parameters have also been used. Strickland et al. (2004) made an attempt to derive the solar flux from terrestrial dayglow observations in the far ultraviolet. The brightest oxygen emissions (red and green lines) have been used by Singh and Tyagi (2002). In each case, the impact of the flux must be isolated and modelled by a kinetic and/or fluid ionospheric and/or thermospheric code.

The importance of these approaches should not be underestimated as they offer an excellent way for validating or refuting solar flux models. Most of them, however, are not suitable for space weather purposes. One of the obstacles is the multiplicity of intricate phenomena. A flare, for example, enhances the XUV-EUV flux, but also increases the electric field, which alters the dynamics of the ionosphere, heating the lower layers and thereby modifying the ion composition and the exospheric temperature, which, in turn, is an input parameter for some thermospheric codes. These processes are so complex and so much entangled that their solutions are not necessarily unique (Lilensten and Blelly, 2002). Moreover, all codes depend on internal physical and chemical parameters (e.g. absorption cross sections, collision cross sections) that are known with limited accuracy.

The thermospheric impact of the variability of the solar flux is equally difficult to use. Culot et al. (2005) have shown that the green line is not sensitive enough to geomagnetic activity in order to be used as a thermospheric tracer for space weather. Let us do a simple calculation for the case of the ionosphere: the primary electron production (due to photoionization) is roughly proportional to the total XUV-EUV solar flux, as it is described by the Beer-Lambert law (Lilensten et al., 1989). The additional production from electron collisions (secondary production) is also sensitive to solar activity. In the E and lower F regions, this additional production may double (quiet conditions) or triple (active conditions) the primary production. At higher altitude, the effect is about constant (30% of the primary production). In the E and lower F regions, the electron density is roughly proportional to the square root of the production (Schlegel, 1988). A variation of the solar irradiance by, say, 33% then results in a variation of the electron production rate by less than 100% (3 times the irradiance variation) and a variation of the electron density of about 10%. This value approximately equals the error bar for the most accurate measurements made by incoherent scatter radars; it certainly exceeds the precision on the TEC, as derived from global positioning measurements. To conclude, even accurate ionospheric measurements presently remain too coarse to evaluate the contribution of various parts of the solar EUV-XUV spectrum. Establishing a correspondence between the two is important for research, but trying to retrieve the XUV-EUV fluxes from their impact is illusory.

5 Measuring the whole spectrum is difficult and expensive

Making continuous and real-time measurements of the XUV-EUV irradiance has always been a challenge. The instruments are costly and sensitive to contamination, their lifetime is limited by degradation, and frequent recalibration is required. In a comprehensive review, Schmidtke et al. (2002) show that the spectral coverage of the solar spectrum in the last solar cycles has been far from complete. This has resulted in a long hiatus known as the "EUV hole" (Donnelly, 1988; Woods et al., 2005) that has lasted until 2002. A list of present and future missions can be found in Hochedez et al. (2006). Even on board SOHO, the spectrum is not fully measured, although several instruments are devoted to its observation. SUMER (Wilhelm et al., 1995) is a normal incidence spectrometer with two alternate detectors working in UV wavelength, from 50 nm to 161 nm. The spatial resolution along the slit has an average value of 1 arcsec and the spectral resolution is about 0.0044 nm. The measurements made by SUMER have been heavily used in the aforementioned works by Warren et al. (1998) and Kretzschmar et al. (2004).

The images taken by EIT (Delaboudiniere et al., 1995) are well known and have largely contributed to the success of SOHO. EIT observes the full disk at 28.4 nm, 17.1 nm, 19.5 nm and 30.4 nm and is a key facility for space weather. EIT, in principle, cannot be used for reconstructing the solar DEM as one of its lines is optically thick. Reconstructions have nevertheless been reported by Cook et al. (1999). Finally, the Solar Extreme Ultraviolet Monitor (SEM) is a transmission grating spectrometer that has been designed to measure the absolute solar EUV flux in the Al bandpass region (17–70 nm) and around the He II line at 30.4 nm (Ogawa et al., 1998).

An outstanding instrument that continuously measures the XUV-EUV spectrum since February 2002 is the Solar EUV Experiment (SEE) on board the TIMED spacecraft (Woods et al., 2005). SEE actually consists of 2 parts, an EUV Grating Spectrograph (EGS) that measures the spectrum from 25 to 195 nm with 0.4 nm spectral resolution and a XUV Photometer System (XPS) that measures from 0.1 to 35 nm with a spectral bandpass of 5 to 10 nm. In the frame of this review, SEE is certainly a unique instrument, and is heavily used (e.g. Dudok de Wit et al., 2005; Kretzschmar et al., 2006; Warren, 2006). Unfortunately, XPS is now partly ineffective.

Two other relevant instruments are the Large Yield RAdiometer (LYRA) and the EUV Variability Experiment (EVE). LYRA (Hochedez et al., 2006) is a VUV radiometer on board PROBA2 (to be launched in 2008) and will measure the spectrum in 4 different bands and with a cadence up to 30 Hz: Lyα (115–125 nm), Herzberg continuum (200–220 nm), Al channel (17–70 nm) and Zr channel (1–20 nm). The EVE instrumental suite (Woods et al., 2006) on board the Solar Dynamics Observatory (SDO) is a heritage from SEE, with higher spectral resolution, higher temporal cadence, and better accuracy. The launch of SDO is planned in 2008, with a nominal lifetime of 5 years. EVE consists of several instruments: the Multiple EUV Grating Spectrograph (MEGS) is a set of 2 spectrographs that measure the 5–105 nm spectral irradiance with 0.1 nm spectral resolution and with 10-s cadence. Part of the MEGS-A CCD is directly illuminated to measure the individual X-ray photons in the 0–7 nm range with 1 nm or better spectral resolution. The EUV Spectrophotometer (ESP) is a spectrograph that measures the solar irradiance in the 0.1–7 nm, 17–34 nm, and 58–63 nm bands to provide solar X-ray measurement shortward of 5 nm.

The SEE spectrograph on board TIMED is currently suffering from growing degradation and even though EVE will soon take over, long-term measurements of the full XUV-EUV-UV spectrum with sufficient spectral and temporal resolution are not guaranteed.

6 It is therefore tempting to deduce the whole spectrum from the measurement of a reduced set of lines

One of the most conspicuous properties of the solar XUV-EUV spectrum is remarkably similar time evolutions of most spectral lines, when properly normalised (e.g. Floyd et al., 2005). This raises the question as to whether one could infer the spectral variability from a small ensemble of lines only. One could, for example, assume that the total solar spectrum is a linear superposition of reference spectra that originate from different regions, such as coronal holes, active regions or a quiet Sun. Knowledge of the relative area (or filling factor) of each of these regions (3 in this example) would then be enough to retrieve the total solar spectrum. Conversely, by measuring the total spectrum and its variability, one could, in principle, estimate the filling factors, which are an important input for EUV irradiance models (Warren, 2006) and also for total irradiance models (Wenzler et al., 2006).

This idea of defining reference spectra has been used in the aforementioned studies by Kretzschmar et al. (2004) and Warren (2006). There are some limitations in this. The first one is the lack of crisp definition of what a quiet Sun actually is. Reference spectra formally cannot be constant and must vary in time because of the heterogeneous and dynamic nature of the solar upper atmosphere. Another problem is the lack of observational data, which hinders the definition of a reference flux for the corona or for active regions. Lastly, the number of reference spectra is not known a priori. These problems can be alleviated by following a more statistical approach, in which the reference spectra are determined by blind source separation techniques. Such techniques have recently been developed for spectral unmixing problems (Moussaoui et al., 2006). Their main assumption is that the total spectrum is a linear combination of the unknown reference spectra. Their objective is to jointly estimate these unknown spectra and their contribution to the total spectrum, using statistical hypotheses such as independence and imposing a structural positivity constraint. Preliminary results have shown that three reference spectra suffice for reconstructing the spectral variability (S. Moussaoui and P.-O. Amblard, personal communication, 2007).

A conceptually different approach consists in retrieving the whole spectrum from the observation of a selected set of lines, spectral bands or proxies. The aforementioned FISM model (Chamberlin et al., 2006), is based on this. Such a reconstruction can be done using either physical considerations, or a statistical approach. Knowledge of the emission intensity of a given ion gives a lot of information about its excitation state. Using quantum mechanics, one can, in principle, recover the other states and therefore the other emission intensities. This property is actually used in the reconstruction of the DEM. Using this approach with the CHIANTI atomic database for emission lines, Kretzschmar et al. (2006) showed that the EUV spectrum can be reconstructed with a relative error smaller than 10%. More important is their result showing that no more than 6 to 10 lines are needed to reach this level of accuracy. By combining this approach with the previous one, one could infer reference spectra from the DEM for various solar regions, and from this reconstruct the total spectrum. An important property here is equality between the DEM of the sum of the contributions and the sum of the DEM from each contribution (Pottasch, 1963). This idea underlies the work by Warren et al. (1998).

The second and more statistical approach is based on data reduction techniques. Dudok de Wit et al. (2005) analysed more than two years of daily-averaged solar spectral irradiance data from the SEE spectrometer on board TIMED using the Singular Value Decomposition (SVD) method (Golub and Van Loan, 2000). The SVD is commonly used in multivariate statistics to replace an ensemble of correlated variables by a smaller set of new variables, whose linear combination captures the main features of the original data. Using the SVD, a basic set of lines was extracted, from which the salient features of the spectral variability could be reconstructed. A first result is that 5 to 8 of these lines are sufficient for reconstructing the spectrum between 25 and 195 nm with a relative error below 7%, in excellent agreement with the study by Kretzschmar et al. (2006). The second important outcome is a strategy for determining the most appropriate lines. For a given number of lines, several possible combinations give almost equally good results. In determining the best combination, it is important to note that the choice of an observational set should be application-driven. Lilensten et al. (2007), for example, determined the sets that are suited for thermospheric studies by determining the impact of individual lines on the ionosphere. The best set consists of H I at 102.572 nm, C III at 97.702 nm, O V at 62.973 nm, He I at 58.433 nm, Fe XV at 28.415 nm, and He II at 30.378 nm. It is noticeable that the HeII line is blended by SiXI line but the two lines behave differently as the first one is optically thick and the second one optically thin. The characterization of the dynamics which is the aim of this set is therefore not affected by this blending.

A third alternative is to use an artificial neural network as a flexible nonlinear model for fitting the XUV-EUV irradiance at given wavelengths, using a set of inputs that could include spectral lines, soft X-ray channels, etc. Such black-box models are now increasingly used for space weather applications, such as the forecast of the total electron content (Tulunay et al., 2006).

All these studies provide a strong incentive for an instrument that would allow the full XUV-EUV spectrum to be recovered in real time from a few channels (spectral bands). Instead of using a full-fledged spectrograph, the flux would be measured by diodes, for which more robust technologies are being developed (Benmoussa et al., 2006). The methods we have described are excellent for nowcasting. Forecasting is a much more challenging task, which not only requires continuous XUV-EUV measurements, but also imaging of the Sun in several wavelengths and a better understanding of precursors. The slowly varying contribution of the quiet Sun is relatively easy to model, but forecasting the impulsive contribution of flares is still beyond reach.

7 Conclusion

The XUV-EUV solar flux is a key parameter for space weather. This quantity is still poorly known and spectrally resolved measurements are scarce. There are several approaches for reconstructing the intensities at all wavelengths, using either proxies or by modelling the impact on the ionosphere. None of them are really suited for space weather applications, even if they all have their advantages, especially for solar-terrestrial research. Determining the XUV-EUV spectrum in real-time (or in near real-time), and for the long term is a real challenge. This objective is now within reach. Forecasting is still outside our current capabilities.

The next decades should see new concepts emerge. Spectro-imaging, even with coarse spatial resolution, would be of great interest for solar physics. As far as space weather is concerned, the reconstruction of the XUV-EUV flux from a linear combination of a few carefully chosen diode measurement would be of considerable interest. Because such an instrument would be lighter, cheaper and more robust than present spectrographs, it could piggyback on other spacecraft. The space weather community will soon have a chance to test this concept thanks to the simultaneous operation of LYRA on board PROBA2 and the EVE suite on board SDO.

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