2. SOLAR ULTRAVIOLET SPECTRAL IRRADIANCE MEASUREMENTS

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ABSTRACT

The solar ultraviolet irradiances performed during the solar cycle 19, 20, 21 and 22 are briefly reviewed and discussed. The 27-day and the 11-year variations are also presented, mainly for solar cycle 21. The analysis of the new measurements currently made from the space shuttle flights and from the "Upper Atmosphere Research Satellite" is still in progress and will improve our knowledge on the solar UV irradiance values relevant for atmospheric studies.

INTRODUCTION

The solar electromagnetic radiation is the primary source of energy for the terrestrial environment. The largest fraction of energy associated with the solar spectrum is situated in the visible. The ultraviolet domain for wavelengths shorter than 320 nm represents only a small fraction (2 percent) of the total incident flux. This spectral range is of fundamental importance for aeronomic processes taking place in the troposphere, the stratosphere, the mesosphere and the thermosphere.
Because of the complexity of the atmospheric processes and the strong interplay and feedback between transport, chemical composition and radiative budget, atmospheric and climate studies should include observations of the ultraviolet solar radiation and its variability, in close relation with the atmospheric constituents which control the penetration of solar radiation. The ozone molecule is a key minor constituent of the stratosphere produced by photodissociation of molecular oxygen by solar radiation of wavelengths shorter than 242 nm. It provides the main heat source through the absorption of solar ultraviolet radiation and thus determines to a great extent the temperature profile in the stratosphere and the general circulation. Ozone therefore couples the stratosphere and the tropospheric climate through complex processes involving radiative, chemical and dynamic effects.

Consequently, the knowledge of solar ultraviolet irradiance values as well as their temporal variations is fundamental in studying the chemical, dynamical and radiative processes in the middle and upper atmosphere. In addition, the study of solar variability is of crucial importance to distinguish between its impact on the terrestrial environment in comparison with anthropogenic perturbations.

Since the solar cycle 20, several measurements of solar ultraviolet irradiance from Lyman α to 400 nm have been performed including observations from balloons, rockets, space shuttle and satellites. Many of these measurements have been reviewed by Simon (1978, 1981), Lean (1987), Rottman (1988), and Brasseur and Simon (1981). In addition, two WMO-NASA assessment reports on stratospheric ozone (WMO, report n°11, 1982; WMO, report n°16, 1986) include solar ultraviolet radiation discussions relevant to stratospheric ozone.

Variations of solar ultraviolet irradiance have also been analyzed in the same aforementioned works. Recently, Donnelly (1988) for the data of the Solar Backscatter Ultraviolet (SBUV) spectrometer on board Nimbus 7 and Rottman (1988) for the data of the Solar Mesosphere Explorer (SME) satellite have reported new insights on temporal variabilities for ultraviolet solar irradiance.

THE H I LYMAN ALPHA EMISSION LINE (121.6 NM)

The Lyman α solar chromospheric lines initiate photoionization processes in the D-region and the photodissociation, for instance, of water vapor in the mesosphere, controlls the ozone budget in this atmosphere layer through the production of hydroxyl radicals.

The irradiance of the H I Lyman α emission line was measured for the first time in 1949 (Friedman et al., 1951). Since that time, many observations have been performed during the solar cycle 19 and 20 and discussed previously (see e.g. Vidal-Madjar, 1977; Simon, 1978; Simon 1980).

Additional observations were performed during the SPACELAB 2 mission in 1985 (minimum of solar activity between solar cycle 21 and 22) and the ATLAS 1 and 2 missions in 1992 and 1993 (solar cycle 22). The Belgian Institute for Space Aeronomy (BISA) has conducted sounding rocket measurements in 1972 (Ackerman and Simon, 1973).

Three data sets have been obtained by satellite, namely the Orbiter Solar Observatory 5 (OSO 5), the Atmospheric Explorer-E (AE-E) and SME, respectively from June 1977 to May 1980 during the rising phase of the solar cycle 21 and since January 1982 corresponding to the declining phase of the same cycle. During the declining phase of solar cycle 22, two instruments on the Upper Atmosphere Research Satellite (UARS), namely the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM), are measuring the UV spectrum since October 1991, including Lyman α.

Although some values are close to 2×10^{11} hv.s^{-1}.cm^{-2} during the minimum of activity between solar cycle 20 and 21, the average values of the rocket measurements made between December 1972 and March 1977 is 3×10^{11} hv.s^{-1}.cm^{-2}. This value has been widely adopted for low solar activity condition. It has even been used as a minimum value (mid 1976) to normalize the AE-E time series.

The 11-year variation range is still uncertain. Most of the observations suggest a factor of 2 for variation over one solar cycle, except the AE-E time series which indicates a factor of 3, but which displays unexplained shifts in measured radiances for several solar emission lines. This phenomena led to criticisms of the AE-E measurements (Bossy and Nicolet, 1982; Bossy 1983). Recent analysis of the SME time series gives a variation factor of only 1.68 from January 1982 to mid 1986.

Therefore, the absolute minimum values as well as long term variations on the activity cycle are still subject to controversy although the reliability of SME data favors the minimum value around 2.5×10^{11} hv.s^{-1}.cm^{-2} and a solar cycle variation less than a factor of 2. This conclusion is supported by other studies, for instance, the data obtained by the Pioneer Venus Orbiter, suggesting a solar cycle variation of 1.8 (Ajello et al., 1987) during solar cycle 21. Nevertheless, a maximum of 5.6×10^{11} hv.s^{-1}. cm^{-2} was measured in 1992 by SOLSTICE (London et al., 1993) leading to a variation of 2.2 between the minimum in 1986 and the maximum of Solar cycle 22.

The 27-day variations are well determined with the recent Fast Fourier Transform (FFT) analysis of the SME time series since 1982 reported by Simon et al. (1987 ; 1993). This relatively large rotation effect must be considered when comparing snapshot measurements. This variation can occasionally reach a maximum of 30 percent (peak-to-peak amplitude) for the strongest 27-day modulation (e.g. August 1982) but is lower than 10 percent for a quiet Sun.

THE 135-175 NM INTERVAL

This wavelength range concerns the photodissociation of molecular oxygen in the lower thermosphere and, consequently, determines the heating range and the atomic oxygen production in that region. Much of the atomic oxygen is transported down to the mesopause and its density must be correctly known as an essential input to middle atmosphere studies.

The first measurements fully relevant for aeronomic purposes were those published by Detwiler et al. (1961), using a photographic detection technique. Nevertheless, keeping in mind the restriction concerning radiance measurements at the centre of the solar disc because of the centre-to-limb variation, the lower values published by Parkinson and Reeves (1969) have been partially confirmed by the irradiation data obtained by Carver et al. (1972), who used ionization chambers on board satellite WRESAT I in two wavelength ranges centered on 145 and 161 nm. In order to improve the knowledge of the absolute scale of the solar irradiation fluxes in this wavelength range, Ackerman and Simon (1973) carried out rocket measurements using photoelectric detection. Their values are in good agreement with those of Parkinson and Reeves (1969) at 171 nm and intermediate between the lowest and the highest data obtained at 145 nm. Further, rocket observations were performed, leading to solar irradiation flux value averaged over 1 nm reported by Rottman (1974) from 115 to 185 nm, by Heroux and Swirbalus (1976) from 121 to 194 nm and by Samain and Simon (1976) from 150 to 210 nm. The two first experiments also used a photoelectric detector. Samain and Simon (1976) deduced the solar irradiance from photographic stigmatic spectra, by measuring the radiance at the solar disc centre and the centre-to-limb variation from the same spectra. They obtained a solar spectrum with a resolution of 0.04 nm. Later, Kjeldseth Moe et al. (1978) also published rocket photographic data of a quiet region located 300 arc second inside the solar limb which were converted into mean intensities using the centre-to-limb variations measured by Samain and Simon (1976). Discrepancies between the aforementioned measurements reach 40% in the 150-160 nm wavelength range where the molecular oxygen photodissociation rate is maximum, and are higher below 140 nm. They could be partially explained by the variability of chromospheric emission lines with the solar rotation although the Lyman a irradiance variations could not exceed 30% as mentioned above. Beyond 160 nm the agreement between all the measurements is better than 30%. In addition it should be pointed out that the solar irradiation flux measured at 171 nm by Ackerman and Simon (1973), Rottman (1974), Heroux and Swirbalus (1975) and Kjeldseth Moe et al. (1978) are practically the same.

During solar cycle 21, seven rocket observations were performed by Rottman (1981), Mount et al. (1980), Mount and Rottman (1983a, 1983b, 1985) from July 1975 to July 1983.

Five additional rocket observations made from November 1978 to December 1984 have also been reported by Mentall et al. (1985) and Mentall and Williams (1988). Their wavelengths range for all published irradiance values starts at 150 nm. All of these rocket observations relate directly to the NIST Synchrotron Users Radiation Facility (SURF) calibration.

Important disagreements are still present in spite of the improvement in calibration procedures illustrated by the quoted accuracy of each observation. The two maximum values obtained in 1979 and 1980 are subject to controversy because they are not supported by the long-term variation deduced from the SME time series discussed later. On the other hand, the interpretation of dayglow measurements at 130.4 nm at solar maximum required solar irradiance values close to those obtained during the declining phase of the solar cycle 21 (Link et al., 1988). In addition, the differences in irradiance values cannot be explained in terms of solar rotation, because such variations do not exceed 14 percent for the C IV emission lines lying in the 150-160 nm interval, for an active Sun (Simon et al., 1987).

In conclusion, the absolute value of solar irradiance between 135 and 175 nm remains controversial and needs further observations. The set of rocket measurements performed between October 1981 and December 1984 are in good agreement, with a standard deviation of only 4 percent for the 150-160 interval. The current observations of UARS will certainly provide more reliable measurements in this wavelength range.

THE 175-240 NM INTERVAL

This wavelength range corresponds to the Schumann-Runge absorption bands and Herzberg continuum of molecular oxygen and is directly related to its photodissociation in the mesosphere and the upper stratosphere. This solar irradiance range is mainly responsible for the photodissociation of molecular oxygen below 90 km which absorbs radiation of wavelengths shorter than 242 nm. This process is responsible for ozone production in the stratosphere. Some minor constituents such as nitrogen oxides, water-vapor and halocarbons also undergo photodissociation in this wavelength range.

The data of Detwiler et al. (1961) already discussed, are the only measurements performed in this wavelength range during solar cycle 19. During solar cycle 20, Samain and Simon (1976), already mentioned, and Brueckner et al. (1976) also determined the solar irradiance fluxes up to 210 nm from radiance measurements of a selected quiet area on the solar disc, using the limb-darkening values measured by Samain et al. (1975). Both used photographic detection techniques and obtained solar spectra with resolutions of 0.04 and 0.007 nm respectively. Other rockets and satellite (NIMBUS 7) measurements from 1978 to 1985 were reported by Mount and Rottman (1983a, 1983b, 1985), Mentall et al. (1985), Mentall and Williams (1988) and Van Hoosier et al. (1988).

Actually, the 175-200 nm wavelength region suffers from relatively higher uncertainties than those quoted for observations made below 175 nm and above 200 nm, except for the SUSIM measurements. For the rocket observations, the uncertainties are between 5 and 20 percent . This may be explained by the more difficult calibration procedure in that spectral range. Mentall and Williams (1988) attempted to solve this problem by using a third mid-range spectrometer providing additional coverage in the overlap region (180-190 nm) of the two other instruments.

Measurements around 200 nm and beyond, corresponding to the so-called UV stratospheric window due to low value of molecular oxygen absorption cross-section and to a minimum in the ozone absorption cross-section, have been performed during the solar cycle 20 by means of stratospheric balloons. These measurements were pioneered by the Belgian Institute of Space Aeronomy (Ackerman et al., 1971) and have been pursued in the 1970's. Measurements reported by Simon (1974) have been adopted during a decade as a reference for modelling purposes, superseding the measurements of Broadfoot (1972).

Several observations have been performed during solar cycle 21. The values of Heath (1980) and Simon et al. (1980) confirm the previous balloon measurements of Simon (1974). The results obtained during the declining phase of solar cycle 21 have been compared with the previous ones and extensively discussed by Labs et al. (1987) when they reported the data obtained during the SPACELAB 1 mission in December 1983 with the Solar Spectrum (SOLSPEC) experiment in which the Belgian Institute for Space Aeronomy was involved. From their comparison with previous data, it appears that the new data harmonize better with the spectral distributions of Heath (1980) and Mentall et al. (1981) than those reported by Mount and Rottman (1983a, 1983b, 1985). However, all absolute values agree within + 5 percent and - 10 percent.

The observations performed during the SPACELAB 2 mission by means of the SUSIM experiment and reported by Van Hoosier et al. (1988) are in very good agreement with the SPACELAB 1 data obtained by SOLSPEC, namely within ± 2 percent. During the solar cycle 22, the Belgian Institute for Space Aeronomy was involved in the ATLAS 1 and 2 missions (experiment SOLSPEC) and the EURECA mission (experiment SOSP). This latter experiment stayed nearly 9 months in orbit before being retrieved by the space shuttle in 1993.

THE 240-400 NM INTERVAL

This spectral region is related to the photodissociation processes in the stratosphere and in the troposphere. The 280-320 nm interval (UV-B) is of fundamental importance for tropospheric chemistry and for biological effects in the biosphere.

This interval has been observed from space (satellite, rocket, space shuttle), balloon, aircraft and from ground based observatory for wavelengths larger than 330 nm (Neckel and Labs, 1984). This latter measurements were performed in the 1960's. The latest measurements were performed by the ATLAS 1 and 2 missions (SOLSPEC, SUSIM, SSBUV), by EURECA (SOSP) and by UARS since October 1991 with the SUSIM and SOLSTICE instruments.

The 240-350 nm wavelength interval has been extensively discussed in the publication by Labs et al. (1987), already mentioned. Since that time, only the SPACELAB 2 observation (SUSIM) in 1985 (Van Hoosier et al., 1988) and SOLSTICE on board UARS since October 1991 results (London et al., 1993) have been reported. Differences with the Neckel and Labs's values (1984) are observed near 400 nm. They cannot be explained at the present time. The results obtained from the latest observations are currently being analyzed.

SOLAR ULTRAVIOLET VARIATIONS

The ultraviolet range of the solar electromagnetic spectrum is characterized by its temporal variations which directly affect the atmosphere. Two time scales are generally considered in relation with aeronomic studies of the middle atmosphere : the 11-year activity cycle and the 27-day rotation period of the Sun.

Because of the difficulty in detecting the solar irradiance variation related to the solar activity cycle, the impact of the 27-day variation associated with the rotation period of the Sun was analyzed in detail. Indeed, observations over short scale periods are by far more accurate in that they avoid the aging problem of the solar instrumentation. These studies are very useful in the validation of photochemical processes.

1. THE 27-DAY VARIATIONS

The 27-day solar rotation variations have been well documented with the SBUV satellite and the SME data base and the current SOLSTICE measurements. The analysis of solar rotation induced variations from the SBUV observations has been reported by Donnelly (1988) showing the great uniformity in the shape of this modulation during the six years of observation from November 7, 1978 to October 29, 1984 for wavelengths between 175 and 285 nm. Several examples of variations in that spectral region have been published by Heath and Schlesinger (1986). The strongest modulation occurred in August 1982, giving a variation of 6 percent at 205 nm.

The SME data base has also been extensively analyzed using the Fast Fourier Transform technique (FFT) to isolate the solar flux modulation related to the 27-day solar rotation The amplitude variations over the full spectral range, namely 115-300 nm, have been deduced for five years of observation from January 1, 1982 to December 31, 1986. The results of this analysis have been reported by Simon et al. (1987 ; 1993). The 27-day modulations at Lyman a and 205 nm show periods of high uniformity in shape like in mid 1982. On the other hand, other periods show striking differences in shape for those two wavelengths like, for instance, in mid 1983 and the beginning of 1984.

The same technique has been applied to the SBUV time series for comparison purposes. The agreement between the two satellites during the overlapping period of time is very good for the strongest modulation taking place on August 1982. However, the average during the declining phase of the solar cycle shows some appreciable differences beyond 240 nm where SBUV data are less noisy than those of SME and below 190 nm where SME gives higher 27-day variations than SBUV, especially for the Si II lines. The agreement is very good for wavelengths between 210 and 230 nm. The best description of the 27-day variations during the declining phase of solar cycle 21 would be provided by the SME data base from 115 to 210 and from the SBUV observation from 210 to 300 nm. The 27-day variations deduced from the observation of SOLSTICE for the time period 26 Nov. 1991 to 31 Dec. 1992 have been recently reported by London et al (1993).

2. SOLAR CYCLE VARIATIONS

Despite of considerable effort during the solar cycle 21, the amplitude of solar variation associated with the 11-year activity cycle is still uncertain. The SBUV spectrometer suffered from severe aging problems, mainly in the reflectivity of the diffuser plate used for solar irradiance measurements. The available data have been accordingly corrected for instrumentrelated changes (Donnelly, 1988) and were analyzed by Heath and Schlesinger (1986). They deduced long-term variations from an empirical relation based on temporal variation of ratios between core and wings irradiances of the Mg II lines at 280 nm. This study is intended to eliminate the effects of instrumental drift and defines the so-called Mg II solar activity index. A composite Mg II index based on NIMBUS 7, NOAA-9 and 11 satellite observation has been calculated and published with the scaling factor for wavelengths from 170 to 400 nm, covering the declining phase of solar cycle 21 and the rising phase of solar cycle 22 (Deland and Cebula, 1993). Balloon measurements at high resolution reported by Hall and Anderson (1988) demonstrate that the value of the Mg II index is very sensitive to unique instrument characteristics (spectral bandpass and line shape). Consequently, the extension of this index to other data sets has to be made very carefully and requires a critical normalization with data overlapping in time with the SBUV observations. On the other hand, the amplitudes of the solar cycle variations deduced from the Mg II index are not fully confirmed by the SME results obtained during the declining phase of solar cycle 21 (since 1982) which lead to lower values in the overlapping wavelength range (160-300 nm). In addition, long-term variations between 115 and 180 nm deduced by comparison between rocket observations made during maximum levels of solar activity, namely 1979 and 1980 (Mount et al., 1980; Mount and Rottman, 1981) and those performed at solar minimum (Rottman, 1981), were of the order of 2 for Lyman α as well as around 150 nm. These high values are not supported by recent analysis of SME data, which imply variations of only 15 percent around 150 nm and of 5 percent between 180 and 210 nm.

CONCLUSIONS

The knowledge of solar ultraviolet irradiance was very poor until 1981. Uncertainties in observations varied between 10 and 20 percent for most of the published irradiance measurements performed from space (Simon, 1978; Simon, 1981). In addition, their divergences were larger than the quoted accuracies and much larger than the accuracies of calibration sources used at that time.

Considering that radiometric transfer sources available in 1980 had uncertainties varying from about 6 percent to 3 percent from 165 nm to 400 nm, the accuracies of solar irradiance measurements were expected to be in the same range. The discrepancies at that time between the accuracy goals and the achieved uncertainties for the data actually approached factors of 2 to 7 depending upon wavelength range and instrumentation. At that time, the Synchrotron Users Radiation Facility (SURF) was not yet used for the calibration of published solar irradiance observations.

More recent rocket observations during the 1980's by the "Goddard Space Flight Center" (GSFC) and the "Laboratory for Atmospheric and Space Physics" (LASP) have been calibrated by using the NIST SURF radiometric standard. This important step forward in the calibration procedure immediately reduced the data uncertainties to ± 8 percent (see the error budget in Mount and Rottman, 1983a).

On the other hand, inflight calibration sources have been developed for the Spacelab 1 and 2 experiments, namely SOLSPEC and SUSIM. They have reported new data referenced respectively to the black body of the Heidelberg Observatory (Labs et al., 1987) and to the SURF (Van Hoosier et al., 1988). Irradiance values are now available with an accuracy from 4 percent (SUSIM) to 5.2 percent (SOLSPEC). The new measurements performed by SOLSTICE are provided with an accuracy of 3 percent.

In spite of the improvements in calibration procedures, significant discrepancies persist between irradiance measurements in the spectral range between Lyman α and 200 nm. This fact is likely explained by experimental problems encountered in that spectral domain. Basic questions, for instance the maximum value of Lyman α, still need to be correctly addressed in the current decade.

If the 27-day variations are well documented with the SBUV and SME observations during the solar cycle 21 and with SOLSTICE during solar cycle 22, the long term variations related to the solar activity still remain uncertain. This is due to large differences between many measurements performed from 1977 to 1985. Nevertheless, good arguments now seem to validate the proposed solar cycle variation deduced from SME. This problem is of fundamental importance in ozone trend studies. Indeed, predictions in total ozone changes during the current solar cycle (its maximum of activity being expected in 1991) give an increase of ozone towards a maximum at that time. This means that the solar cycle variation in ultraviolet irradiance will counterbalance the predicted decrease due to anthropogenic chlorine compound emissions. After 1991 the total ozone column is decreasing again with a rate still enhanced by the decline in solar ultraviolet irradiance. Consequently, reliable observations of solar variation with a precision of 1 percent over a half solar cycle are needed to quantitatively discriminate between natural changes and anthropogenic perturbations in the middle atmosphere composition. This is the objective of the two solar experiments SOLSTICE and SUSIM, onboard UARS, and of the Space Shuttle missions with the SOLSPEC, SUSIM and SSBUV instruments. First results on temporal variations of solar UV irradiance measured by SOLSTICE have been very recently published by London et al. (1993).

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