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Solar UV variability

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Abstract. The ultraviolet part of the solar spectrum is unique. Sandwiched between the relatively stable visible radiation and the highly variable energetic radiation short of 1000 Å, the EUV and the X-rays, it exhibits a small but significant variation on different time scales. Further, solar UV radiation has an important influence on the earth's atmosphere, being responsible for the energetics and dynamics of the so called middle atmosphere (the height region of 10 kms to about 100 kms). Part of this spectrum has an impact on the biosphere as well. Recent developments related to the ozone depletion and the global warming phenomena have made study of solar UV radiation and its variability an important topic of current day research.

Measurement of solar UV radiation spectrum had to await the availability of space platforms and a reliable quantitative assessment of its variability has become possible only in the recent past. Rocket experiments and data from the Atmospheric Explorer Satellites and the SMM and SME satellites could establish the solar UV spectrum and its short term variabilities, e.g. 27 day rotation. Problems related to degradation of satellite instrumentation plagued a reliable quantification of longer term changes, such as the eleven year cycle. However, in recent years several modelling efforts and improved satellite instrumentation have overcome these difficulties to a great extent. The present paper discusses these developments.

1. Introduction

Solar ultraviolet radiation (λ < 400 nm) which constitutes only about 10% of the total electromagnetic flux emitted from the Sun, is responsible for most of the chemical, dynamical and radiative processes that take place in planetary atmospheres. The more energetic part of this radiation (λ < 100 nm) in the EUV and X-ray region ionises the atmospheric constituents and produces the ionosphere. At longer wavelengths several other photon induced processes, such as absorption, dissociation and excitation take place and give rise to a number of aeronomic phenomena. In the case of the earth's atmosphere the wavelength region of 100-300 nm plays a major role in determining the atmospheric structure, energetics and dynamics. The major features in the earth's atmosphere are absorption by molecular oxygen in the wavelength region 100-200

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nm and by ozone in the wavelength region 200-300 nm (Table 1). The latter is responsible for atmospheric heating in the 20-60 km region of the atmosphere, the so called stratosphere and provides the major driving force for most of the dynamical and electrodynamical processes in the atmosphere.

The ultraviolet part of the solar spectrum emanates mostly from the photosphere, but there is a significant chromospheric contribution as well. The spectrum undergoes a major transition in the 200-300 nm region (Fig. 1). At $\lambda \gtrsim 300$ nm the irradiance is mostly from the photosphere and the equivalent temperature is around 5600°K. At $\lambda \lesssim 200$ nm the spectrum is characterised by increasing dominance of emission lines riding over the underlying continuum which has an effective temperature close to 4700°K. The 200-300 nm wavelength region, generally referred to as the MUV region, is the transition region where the effective temperature undergoes large variations and is highly wavelength dependent (Fig. 1b). Solar UV flux undergoes a significant variation due to changing levels of solar activity, most prominent features being the 13 day and the 27 day rotation periods and the 11 year solar cycle (Lean 1987, 1991). The variability is wavelength dependent. The changes in the MUV region are not so drastic as those in the EUV and X-ray regions (Table 2). Nevertheless, these changes are important since they produce significant changes in the middle atmospheric temperature and dynamics as well as the photochemical state of the atmosphere including trace gas abundances, such as O_3, O, NO_2, CH_4. With the advent of satellites, there is now reliable observational data for solar activity induced changes in stratospheric ozone, middle atmospheric temperatures and even dynamics (Hood 1987; Keating 1987; Hood et al. 1991, 1993). There are several modelling efforts to estimate changes in middle atmospheric structure and composition due to changes in solar UV irradiances (e.g. Brasseur et al. 1988). In recent years it has become very important to have a reliable and quantitative estimate of solar UV irradiance changes due to solar activity and estimate their impact on middle atmospheric structure and composition in view of the major developments in Atmospheric Sciences, such as the long term Ozone depletion (WMO 1995) and Global warming phenomena (IPCC 1996).

2. Solar UV and EUV irradiance measurements

Radiation at $\lambda < 290$ nm is almost completely absorbed by the earth's atmosphere. Hence measurement of the solar spectrum in the UV and EUV region had to await the availability of space platforms (Subbaraya 1995). Even though the first rocket measurement of the solar ultraviolet spectrum was made in 1946 (Baum et al. 1946), the first complete spectrum of the solar UV and EUV radiation down to 17 nm was made in 1962 (Tousey et al. 1964). Since then a number of rocket and satellite borne measurements of solar UV and EUV flux have been made (Hinteregger 1965; Broadfoot 1972; Heath 1973; Heath et al. 1984; Mount and Rottman 1983; Rottman 1988). However, most of the earlier measurements gave information on the nature of the solar spectrum. Reliable and absolute measurements of solar UV irradiance became possible only in the late seventies and the eighties. These measurements showed that solar UV irradiance undergoes both short term as well as long term changes most prominent of them being those associated with solar rotation 13 day and 27 day periods and the revolution cycle ~11 year period. While it has been possible to quantify the shorter time scale variabilities, it has been difficult to make a reliable

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Table 1. Absorption of solar radiation in the earth's atmosphere.

Wavelength region	Fraction of solar energy	Altitude level at which it is absorbed	Primary absorbing mechanism	Percentage of energy absorbed
λ < 100nm	3 parts in a million	90-200 km	Ionisation of atmospheric species	100%
λ100-200 nm	100 parts in a million	50-100 km	Photodissociation of oxygen molecule	100%
Lyman-alpha (121.6 nm)	a few parts per million	60-90 km	Ionisation of nitric oxide	100%
λ 200-310 nm	1.75%	30-60 km	Photodissociation of ozone	More than 95%
λ310-700 nm	48%	--	--	Very little absorption
λ > 700 nm	50%	0-10 km	Absorption by water vapour	10-15%

Table 2. Variations of solar UV flux.

	11 year cycle	27 day solar rotation
Lyman α (121.6 nm)	~100%	~50%
140-150 nm	~100%	~ 30%
150-170 nm	~50%	~10%
170-180 nm	~20%	~1%
180-200 nm	~10%	<1%
200-300 nm	Decreases rapidly with increasing wavelengths	

estimate of the longer time scale variabilities (11 year cycle and longer) due to problems connected with the satellite instrument degradation (Heath and Schlesinger 1986; Lean 1988; Lean 1991). However, in recent years, these problems have been well understood and effective remedial measurements are being undertaken in the current satellite instrumentation (Herman et al. 1991).

3. Indices of solar activity

A number of proxy solar activity indices have been in use to study solar UV variability and its effects on atmospheric parameters. They are (1) Sunspot Number, (2) 10.7 cm radio flux, (3) the

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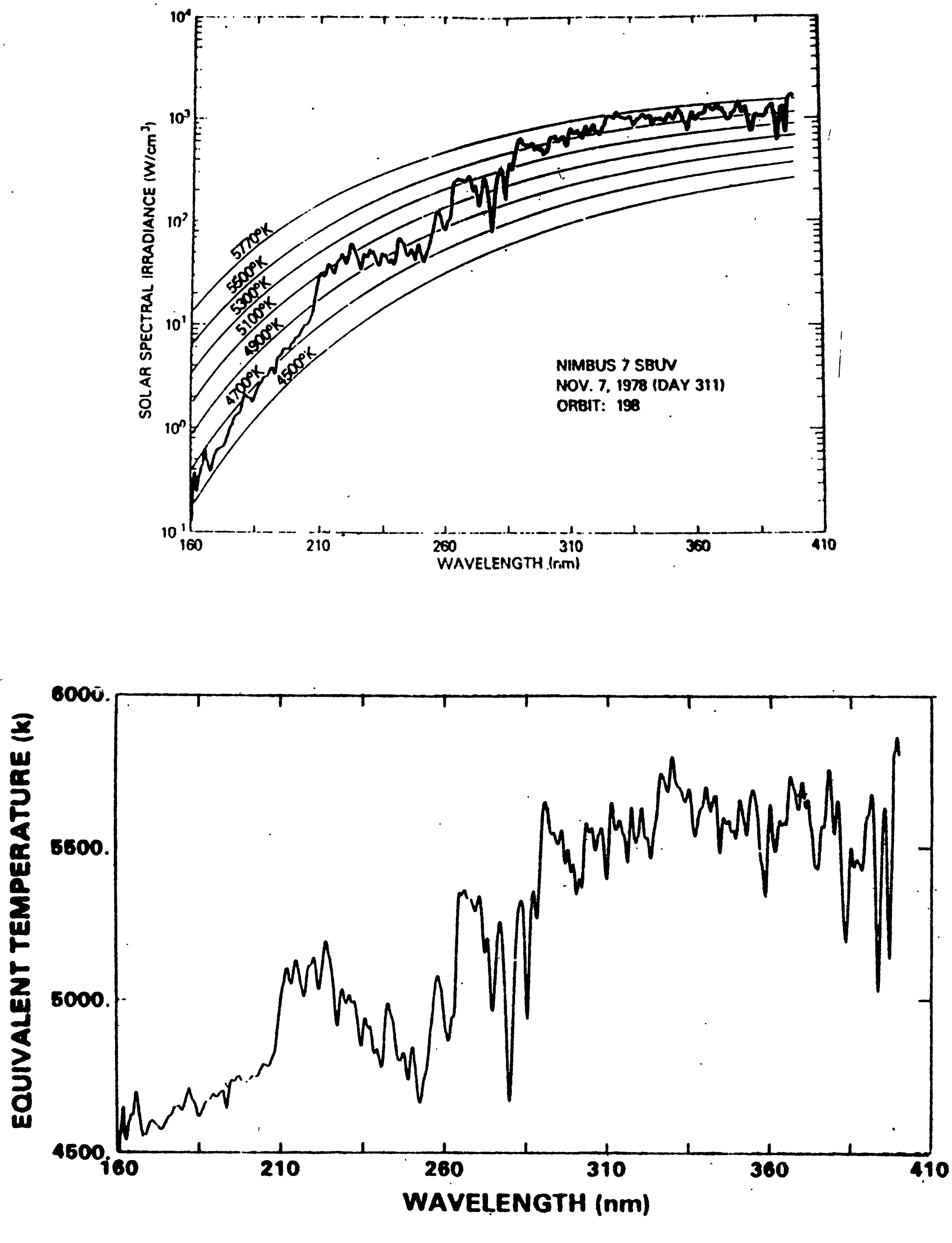

(b)

Figure 1. (a). Solar ultraviolet irradiance as a function of wavelength measured by the Nimbus - 7 satellite on November 7, 1978 (Heath and Schlesinger, 1986). (b). Equivalent brightness temperatures for the above spectrum.

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full disk CaK line intensity at 393.4 nm and (4) the Helium 1083 nm full disc line width. They all show good correlation amongst themselves as well as with solar UV fluxes. The major advantage with these indices is that they can be monitored from the ground. Since most of the solar flux variability is attributed to magnetic activity on the sun the sunspot number can be good but only a qualitative index. The other most commonly used index, the 10.7 cm radio flux originates primarily in the transition region and the corona and hence is a good index of solar X-ray variations (and to some extent EUV). It has been extensively (and successfully) used in D region ionospheric studies. Donnelly (1983) has shown differences in the features of 27 day rotation for 10.7 cm and UV radiation and attributed this to the differences in the altitude of emission of these radiations. The CaK line emission has been extensively used as an indicator of stellar activity. Both the He 1083 nm and the CaK full disc emission at 393.4 nm emanate from the chromosphere and are influenced by conditions in the corona. Hence they are excellent indicators of solar activity and are useful for solar EUV and X-ray variation studies. The UV flux at $\lambda < 210$ nm is found to be well correlated with the CaK line emission (White et al. 1986). The CaK index has been used (Cook et al. 1980), to construct a 3 component empirical model of solar UV variability. This consists of a quiet sun component, a component due to plages and a third component which is vaguely termed as network component.

While most of these been in use for interpretation of atmospheric variability, it has been realised that they are inadequate for a quantitative estimation of solar UV variability, especially the wavelength region of 200-300 nm which is important in the middle atmosphere. This has become increasingly evident over the last ten to fifteen years when sufficient amount of reliable observational data calibrated for absolute fluxes became available during solar cycle 21 and 22.

4. The Mg II Index

Heath and Schlesinger (1986) developed an index based on the core to wing ratio of Mg II doublet at 280 nm using data from Nimbus 7 satellite which is more suitable for study of solar UV variations. The wavelengths chosen are 279.8 nm, 280.0 nm and 280.2 nm. This has several advantages over the CaK line intensity because (1) it is a much stronger emission than the CaK line, (2) being a ration, its measurement is less affected by satellite instrument degradation and most importantly (3) its emission region is the same as for UV and the brightness temperatures are close to that of the continuum in 200-300 nm region (Fig. 1b). UV irradiance for several solar rotations were carefully analysed, ratio of the Mg II core intensity to that at the nearby continuum was determined and the ratio was compared with the UV irradiance data and it was shown that this index could be more useful quantitatively than the other indices for developing an empirical model for changes in solar UV suitable for middle atmospheric studies. Heath and Schlesinger demonstrated that this new index is a good indicator of solar activity, is well correlated with other indices of solar activity currently in use and also showed that it represents solar UV variations much better. The Mg II index variation was found to be 8% from solar maximum to minimum during solar cycle 21 and 9% during solar cycle 22. Solar UV variation at 205 nm was found to be 10% ± 1% for solar cycle 22. Hence Mg II index is well correlated with the solar UV irradiance data.

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Using the data from Nimbus-7, NOAA-9 and NOAA-11 satellites for the period 1978-1992, Heath and Schlesinger (loc cit), Deland and Cebula (1993) developed a time series of the Mg II index. Fig. 2 shows time averaged data of the Mg II index for the period 1978 to 1992 removing the 27 day period to show the 11 year cycle only. Further, Deland and Cebula (loc cit) developed scale factors for the entire wavelength region 170-400 nm with Mg II index as the base so that given the Mg II index variability, the entire solar UV and EUV irradiance variability could be studied.

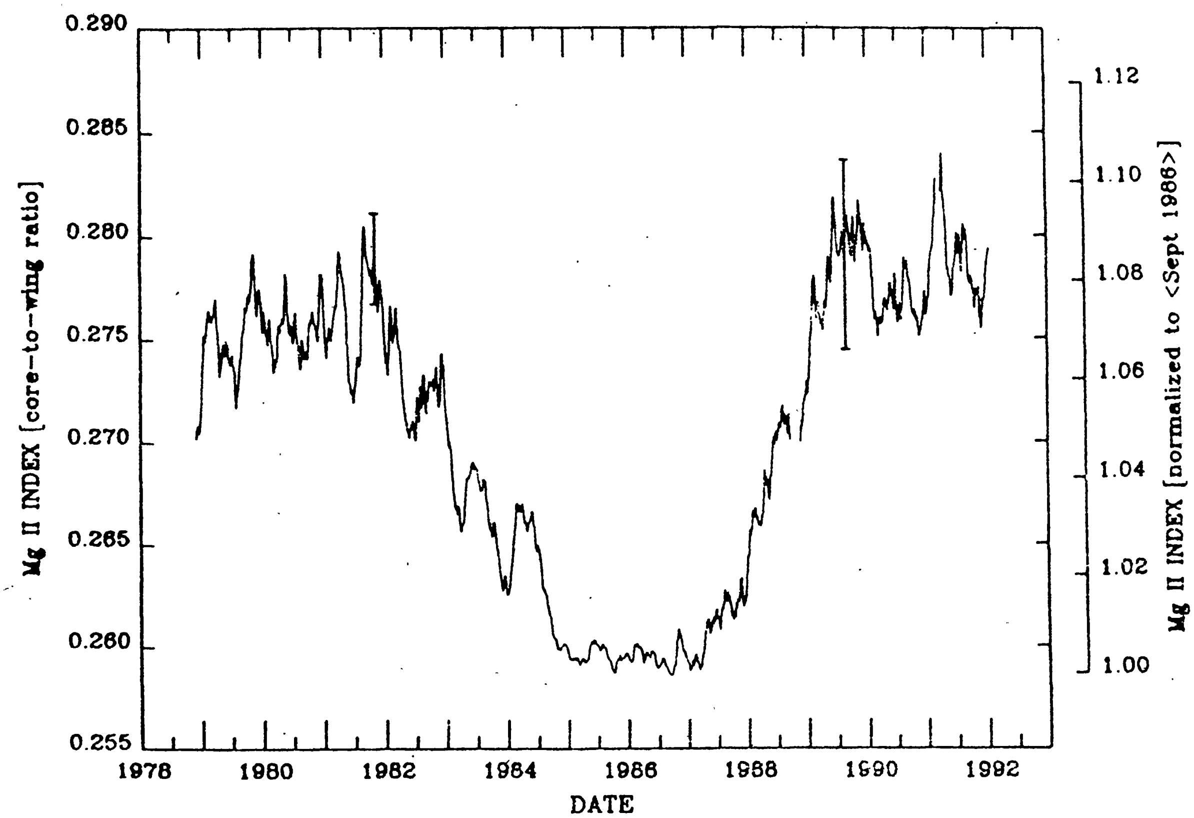

Figure 2. Time series of the Mg11 index (Deland and Cebula 1993).

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5. Recent developments

The UARS satellite launched on 12 September 1991 carried two instruments for solar ultraviolet radiation measurements. They are the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) and the Solar Stellar Irradiance Comparison Experiment (SOLSTICE). Continuous measurements of solar UV flux in the spectral range 115-420 nm are available since October 1991. This data set is capable of long term precision close to 1% in the 200-300 nm region and 3-5% at Lyman-α (121.6 nm) Rottman et al., 1993). Cebula et al. (1996) have shown that data from different instruments and different sensors agree within ± 3%. Hence there now exists more accurate and reliable data on solar UV irradiance which can be used for study of variability related to the 11 year cycle. Using the data from the UARS instruments, Chandra et al. (1995) studied the solar UV irradiance variability during the declining phase of the solar cycle 22. It was found that during the declining phase of the solar cycle 22 the scale factors were somewhat larger than those for solar cycle 21 especially at lower wavelengths $\lambda < 200$ nm. At Lyman -α wavelength the ratio was almost 1.5.

Further study has been hampered due to the prolonged minimum of the solar cycle 22 during the past few years. In the next few years when the solar activity picks up, it needs to be seen how the Mg II index correlates with solar UV irradiance variability and the applicability of Cebula and Deland scale factors for different solar cycles needs to be established. The fact remains that the above scale factors were obtained from study of solar rotation and are being extrapolated to the behaviour of the revolution cycle. The relative distribution of the plages and the faculae and their relative contribution to the short term and long term variabilities still is not fully understood. Further, the relative distribution of the active spots on the sun's disc for different solar activity cycles also needs to be quantitatively established. Hence quantitative study of solar UV irradiance variability and established. Hence quantitative study of solar UV irradiance variability and establishing an empirical model suitable for study of the earth's atmosphere is still a topic for future research. Further, such studies are now possible with the continuous monitoring of solar spectral irradiance using reliable satellite-borne instrumentation.

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