SOLAR IRRADIANCE BELOW 120 nm AND ITS VARIATIONS*

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Abstract. The solar irradiance below 120 nm was first predicted by astronomers. Since its accurate measurement required the solution of a variety of technological problems, little is known about the variability before 1972, though for more than two decades data have been collected. Therefore, on a quantitative basis only a very rough picture can be given for the solar cycle 19. Also, not enough data with sufficient absolute accuracy are available to describe the solar EUV flux variations of the solar cycle 20, especially during the period of solar maximum. However, due to technological improvements of space and laboratory instrumentations, an almost complete set of data has been obtained from 1972 to date. These observations exhibit strong differences of the flux variations from solar cycle 20 to 21. – For the theoretical and for semi-empirical treatments of many aeronomic processes controlled by the solar EUV radiation, its adequate representation e.g. as indices is required. The problems involved and possible solutions are discussed. Results from some relevant aeronomically oriented computations based on variable solar EUV fluxes are presented.

1. Introduction

Astronomers were the first predicting solar EUV radiation using a solar black body model of 5000–6000 K to describe the emitted flux at short wavelengths. The application of these results to the Earth (Elias, 1923) computing the ion-electron production profiles in an isothermal atmosphere provided ionization equilibrium profiles before the ionospheric layers were discovered. This study was performed on a qualitative basis.

Quantitative treatments of this problem became possible after thorough ionospheric observations. In order to bring the latter in agreement with the black-body model of the Sun for the EUV spectral region, an 'ultraviolet excess factor' (Saha, 1937; Kiepenheuer, 1945) had to be introduced being as large as 10^6.

Comparison of the black body temperatures as derived from measurements in the visible spectral region with those in the far ultraviolet, e.g. between 300–200 nm, show that the latter ones were significantly lower. Close to 200 nm the temperatures derived were still lower, close to 4000 K. However, for wavelengths below 200 nm temperatures became higher. The interpretation of measurements in the soft X-ray region provided temperatures up to 20×10^6 K as derived from radiation analysis. Thus a very broad temperature range is found on the Sun originating at different atmospheric layers. Bearing in mind the local inhomogenities of these layers and the changing solar activity with time, a strong variability of the corresponding solar radiation as generated in the chromospheric and coronal regions is to be expected.

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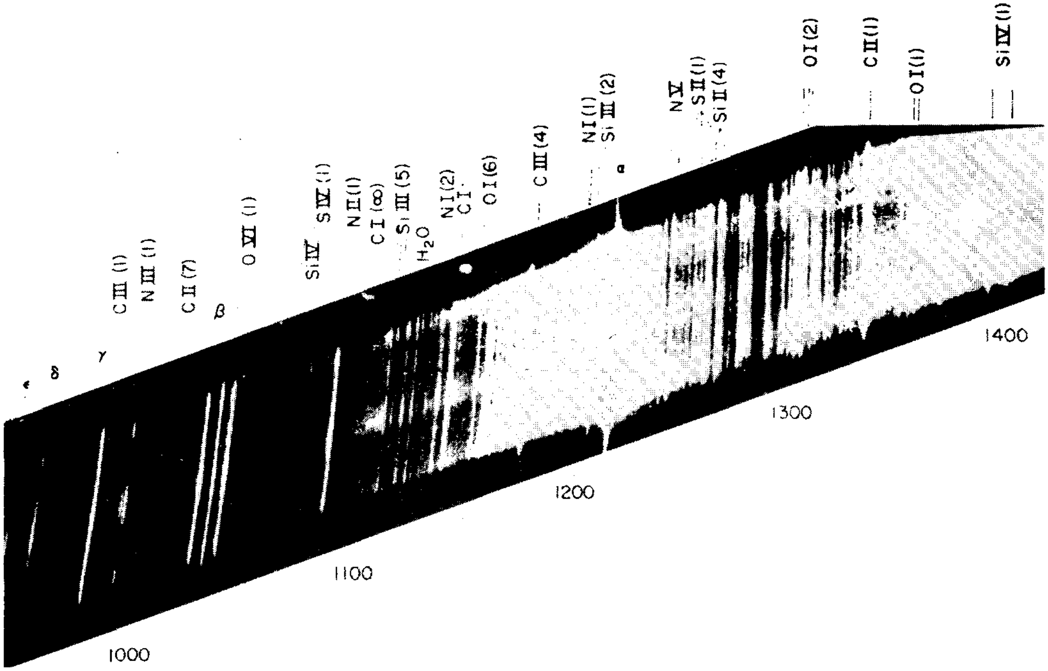

Fig. 1. First photographic measurement of the solar spectrum below 120 nm (April 19, 1960, WSMR, NRL) (Detwiler *et al.*, 1961, in Hinteregger, 1963).

2. Spectral Signature of the Solar Radiation below 120 nm

The solar radiation below 120 nm is generated in chromospheric and coronal regions. The first measurement was performed by Johnson *et al.* (1958) photographing the emission spectrum down to 97.7 nm. Figure 1 shows the most intense features in this spectral region with emission lines from atoms and ions such as H I, C III, N III, Si III, and O VI being dominant. However, the technique based on photographic recording is limited by the straylight background (since the Schumann film is also sensitive to visible light, more than 7 orders of magnitude of energy in the visible compared to emissions close to 100 nm have to be kept off the film), the low temporal resolution, the low absolute accuracy, and the small dynamic range. In general, for quantitative measurements of the variability of the solar radiation below 120 nm the photoelectric techniques has proven superior (Hinteregger, 1963). This is well demonstrated in Figure 2 which compares a photoelectric (upper part) and a photographic (low part) recording covering the spectral range between 60 and 90 nm (Hinteregger, 1963). As seen in Figure 2 the Lyman continuum of the hydrogen atom is the most intense continuous feature of this spectral region. In addition, less intense continua exist from C I between 110–95 nm and He I between 50.4–45 nm.

With decreasing wavelengths more emission lines from higher ionized atoms such as He II, O II–V, Ne VII–VIII, Mg IX–X, Fe IX–XII up to Fe XVI appear down to 10 nm.

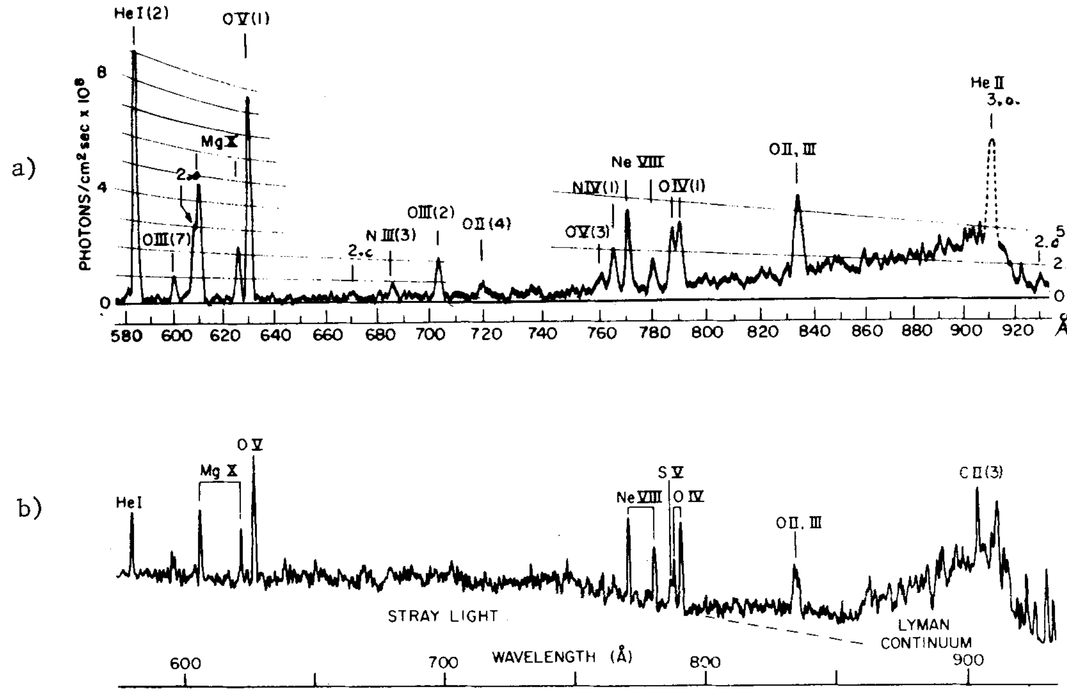

Fig. 2. Comparison of spectral recording techniques: (a) Counter spectrogram (Aug. 23, 1961, AFCRL); and (b) densitometer record (April 19, 1960, NRL) (Hinteregger, 1963).

The soft X-ray region below 10 nm down to 2.5 nm is difficult to detect, since the energy of the emission lines is lower by orders of magnitude as compared to the 18–31 nm spectral region. Based on photographic recording, up to 13 orders of magnitude of visible light compared to weak lines between 10–4 nm are taken off the film either by thin film filter techniques (Freeman and Jones, 1970) or by the sophisticated diffraction filter techniques (Schweizer and Schmidtke, 1971; Schmidtke and Schweizer, 1972). Again, the emission identified stem from highly ionized atoms.

Below 2.5 nm Geiger counter techniques with Bragg crystal spectrometers or rather low resolution proportional counter techniques are applied to record characteristic X-ray emissions or X-ray continua.

The X-ray emission is strongly localized on the solar disc. It is mostly generated in active regions, similar to the emissions of Fe XVI ions. The area of origin of the different emissions is larger when the excitation energy necessary for the photon generation is lower. Moreover each emission, even each of the resonance lines is distributed over the solar disc in a different way (Figure 3).

Summarizing the spectral features below 120 nm, a great variety of emission spectra and continua is generated in the chromospheric and coronal layers of the Sun, the transition-region included, at plasma temperatures ranging from 8×10^3 to 30×10^6 K. Taking into account the non-uniform distribution of solar activity with

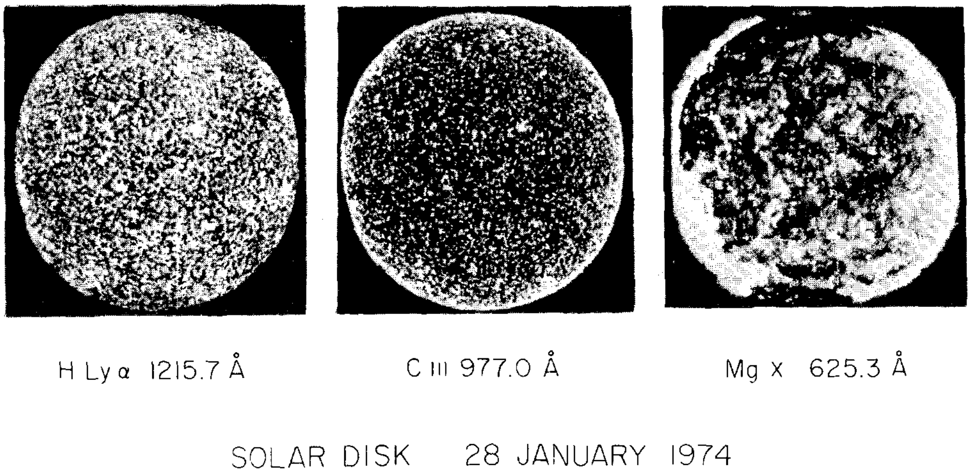

Fig. 3. Spectroheliograms representing chromospheric, transition-region and coronal emission lines (Timothy, 1977).

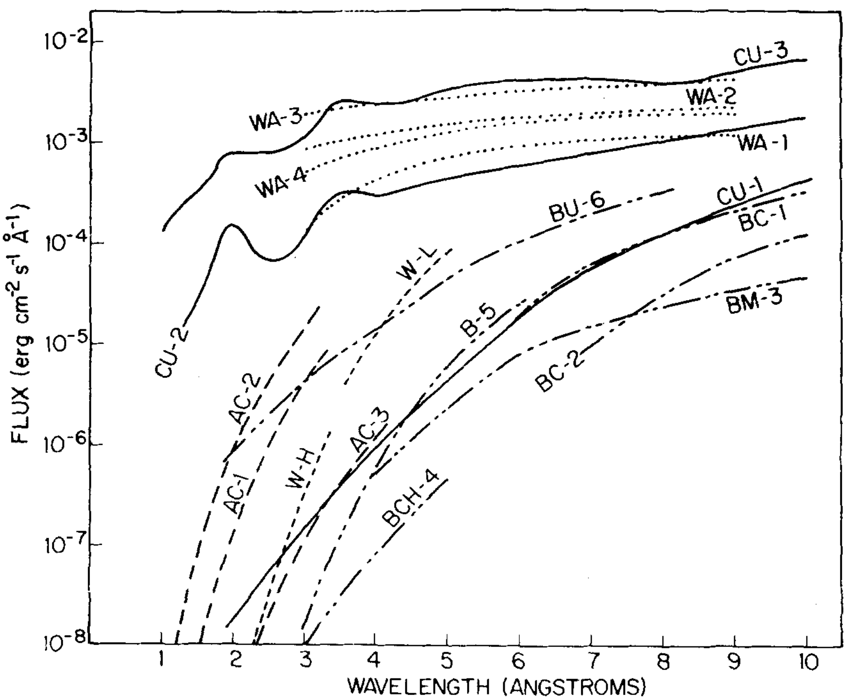

Fig. 4. Variability of the solar X-ray spectral region (Kreplin *et al.*, 1977). The curves represent measured fluxes at different times.

respect to space and time, a great variety can be expected with respect to the variability of the numerous emissions.

3. Variability of the Solar Irradiance below 120 nm

During solar flares and during high levels of solar activity X-ray radiation is an important source of ionization in the ionospheric D-region of the terrestrial atmosphere. For this reason the variability of the solar X-ray radiation is measured from rockets and satellites. Of special interest are the measurements aboard SMS-1 and 2 (Synchronous Meteorological Satellites) and GOES-1 (Geostationary Operational Environmental Satellite). The strongest temporal changes in the spectral range below 120 nm occur in the X-ray region (Delaboudiniere *et al.*, 1978). The variability exceeds five orders of magnitude on a solar cycle time scale (see Figure 4). During flares changes by two orders of magnitude are often measured on a time scale of seconds (Kreplin *et al.*, 1977).

Little is known concerning the variability in the soft X-ray region between 2.5–15 nm. There is too little energy emitted from the Sun to control any geophysical effect of interest. Also, the technical problems involved in continuous measurements are rather difficult to solve. For these reasons this field of research is almost abandoned now. The last published measurements were made in 1972 (see Figure 5 for an intercomparison of different measurements), and consequently, not much is known with respect to the variability. Figure 6 summarizes our knowledge of the spectral irradiance variability in this wavelength range.

At longer wavelengths (15–120 nm) the situation is quite different, because this spectral range is very important for the aeronomy of the upper atmosphere and

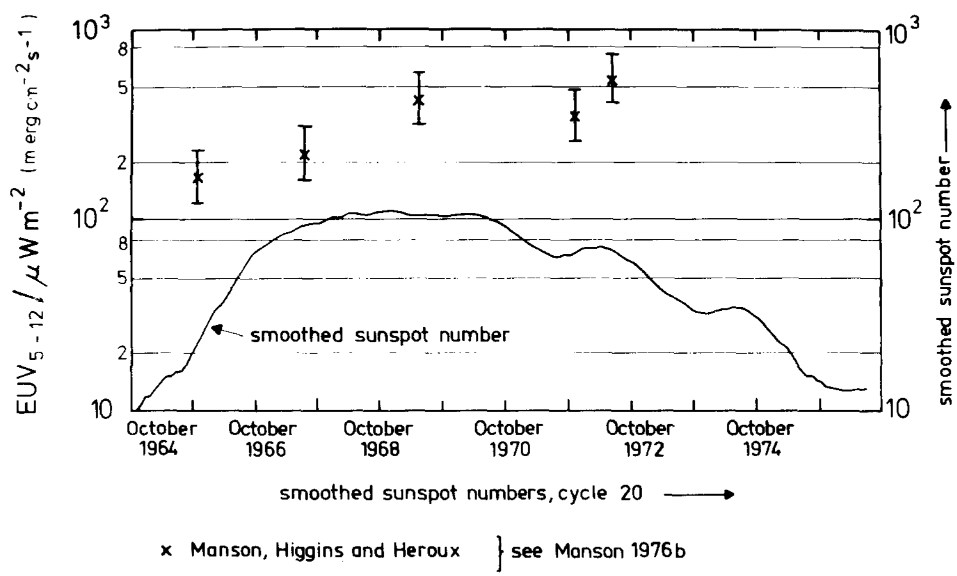

Fig. 5. Measurements in the wavelength range 5–12 nm (Delaboudiniere *et al.*, 1978).

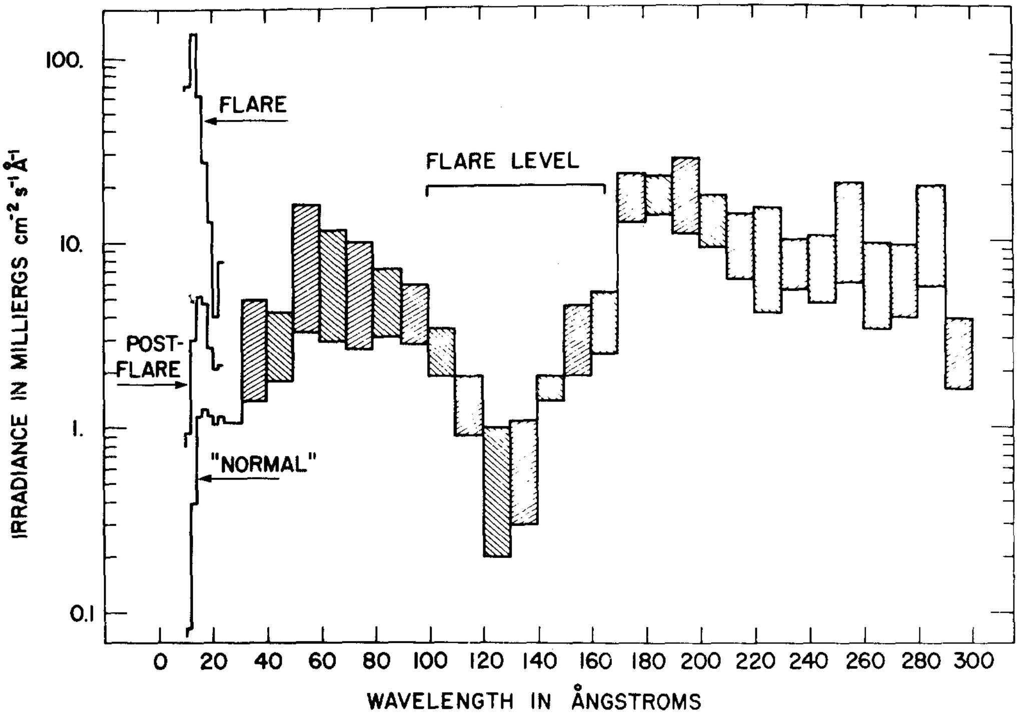

Fig. 6. Solar spectral irradiance between 1–30 nm (Manson, 1977).

hence for satellite orbit predictions. Therefore, the necessity for monitoring the solar EUV flux continuously has been recognized for a long time. Many technological problems, especially with respect to absolute calibration had, however, to be solved (Hinteregger, 1963; Delaboudiniere *et al.*, 1978; Schmidtke, 1978).

Systematic rocket measurements for aeronomy purposes were performed first by Hinteregger (1961). From subsequent measurements a tabulation of the solar EUV flux was presented (Hinteregger *et al.*, 1965). Though some variability of the radiation was expected from the interpretation of measurements on the OSO-1 satellite (Neupert *et al.*, 1964), no estimate could be presented in the tabulation. For this reason the tabulation was used as an 'EUV standard flux' for many years.

With the operation of the EUV spectrometer aboard the OSO-3 satellite in 1967 (Hall and Hinteregger, 1970) and of the 30.4 nm monochromator aboard the OSO-4 satellite in 1967 and 1968 (Timothy and Timothy, 1970) short-term (for periods of 5–10 min) and medium-term (for periods of a solar rotation) variations have been observed. On a relative intensity scale the short-term variations range up to about 25% of the total EUV-flux with different variations for each solar emission. A total flux variation of up to 40% has been measured during solar rotations (Hall and Hinteregger, 1970). Examples are presented in Figure 7. Similar levels of variation are reported from later missions for short events (Figure 8), but those measurements

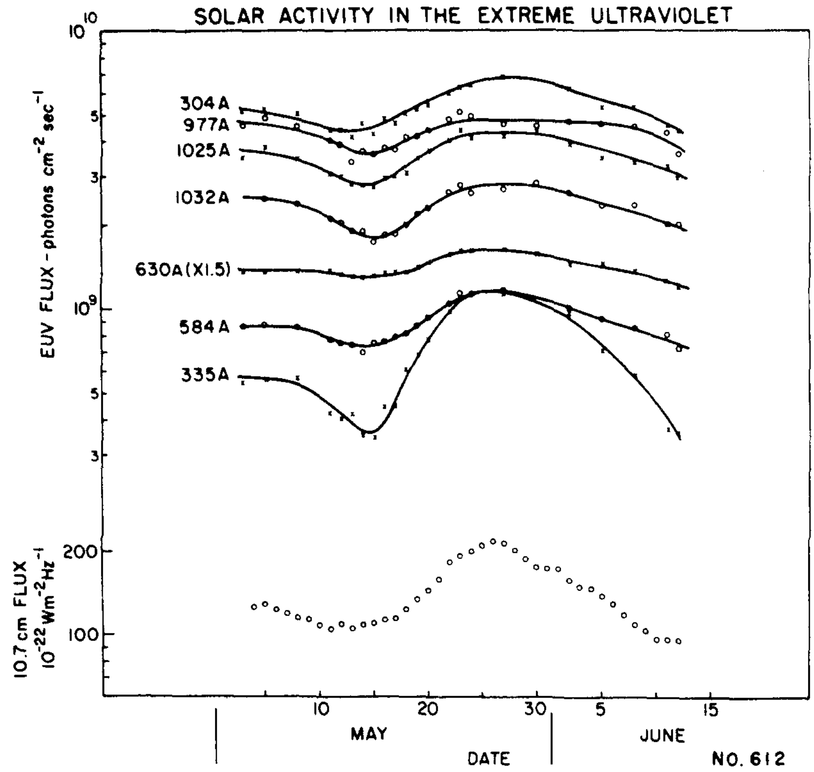

Fig. 7. Variability with solar rotation (Hall and Hinteregger, 1970).

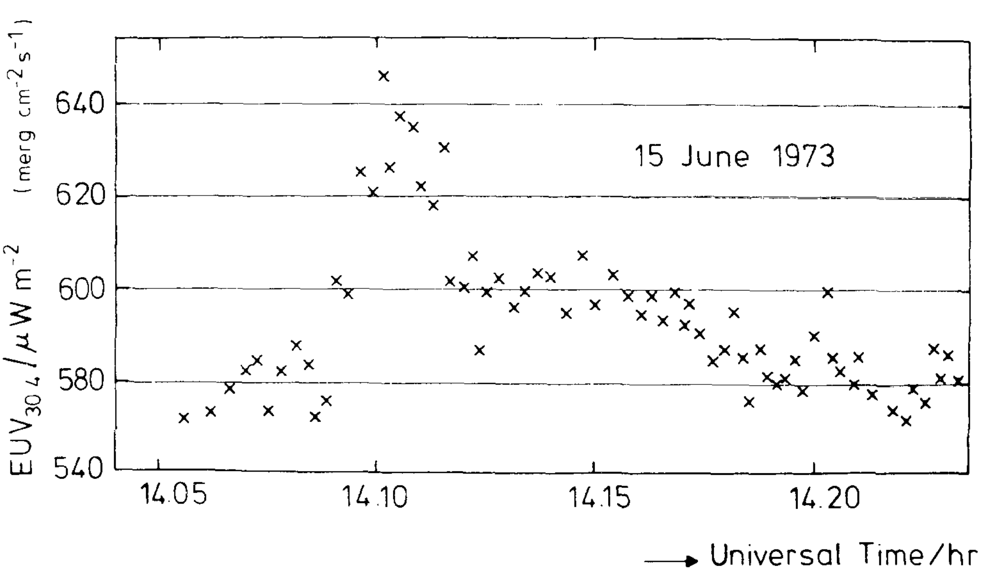

Fig. 8. Solar flare recorded at 30.4 nm (Schmidtke, 1978).

represent a small fraction of the total time period only. Therefore, the numbers given probably do not represent the actual maximum variations.

After short-term and medium-term variations have been observed for different levels of solar activity, the determination of long-term variations over periods of the order of a solar cycle revealed technological problems related to the calibration of the instruments and to the changes of calibration parameters with time. With an uncertainty of the laboratory calibration of about 10–15% and a more severe error source due to the calibration parameter changes during instrumental spacecraft integration and launch as well as during the mission, the best overall accuracy of the flux determination probably is about 30%, i.e. about the same order of magnitude as one of the estimates for the total long-term variation during solar cycle 20 (Hinteregger, 1978). From AEROS-A measurements (Schmidtke, 1978) a decrease of about 30% of the total flux during the period of the declining cycle 20 from December 1972 through August 1973 was derived in the long-term component with a spectrometer applying an inflight calibration of the multipliers. These measurements were, however, inconclusive with respect to the changes from solar maximum. Other measurements did not indicate variations (Heroux and Higgins, 1977) exceeding the calibration uncertainties between different rocket flights. On the other hand the flux ratio of the emissions of Fe XV at 28.4 nm and He II at 30.4 nm is a good qualitative indicator of solar activity. During solar cycle 20 this ratio changed by about one order of magnitude (Figure 9). At this time quantitative numbers concerning the variability of the total EUV flux during the past solar cycles cannot

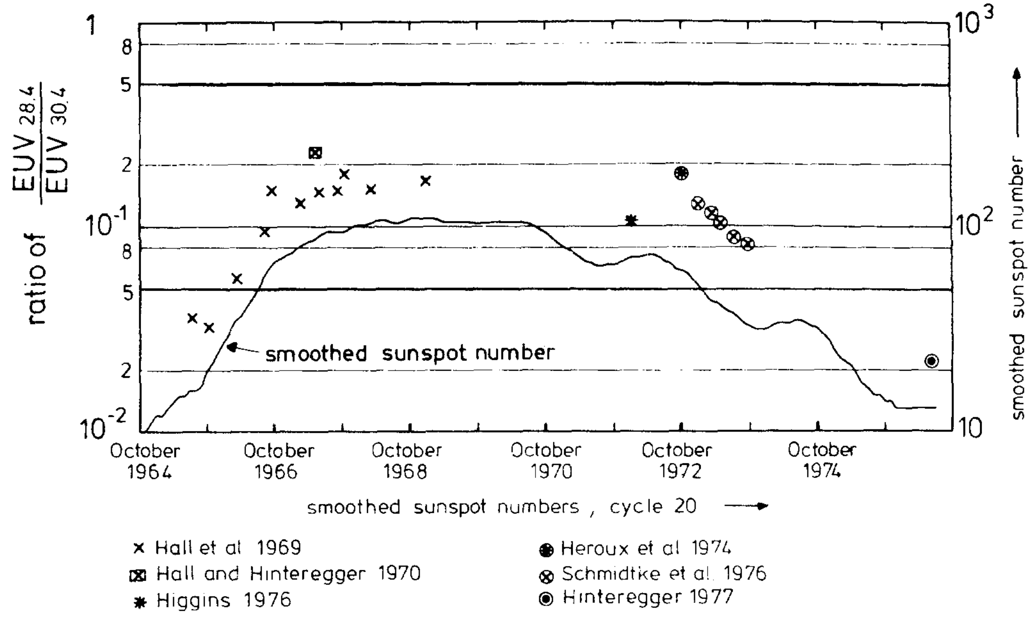

Fig. 9. Solar cycle variation of the index ratio $EUV_{28.4}/EUV_{30.4}$ (Schmidtke, 1978).

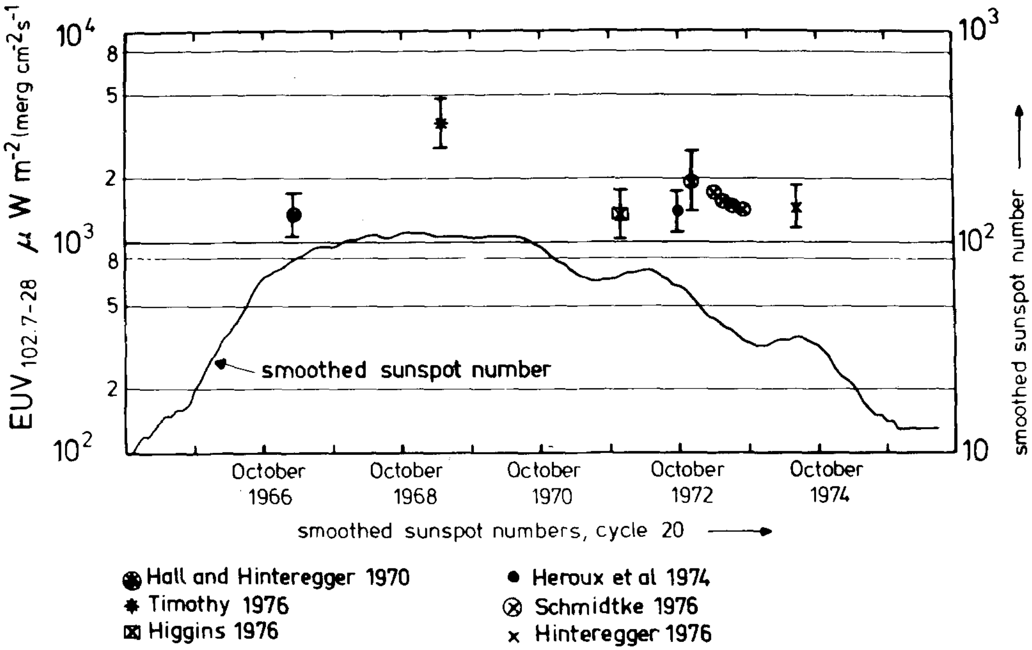

Fig. 10. Measurements of the total EUV flux during solar cycle 20 (Delaboudiniere *et al.*, 1978).

be derived, neither from this ratio nor from any other set of data (Figure 10). This is a remaining dissatisfactory fact.

With the missions of the aeronomy satellites AEROS-A and -B and the Atmospheric Explorers C and E this situation has greatly improved since the end of 1972. Since then almost continuous measurements are performed (Schmidtke, 1976; Schmidtke, 1979a; Hinteregger, 1981) with, for example, data being collected for more than five years by Atmospheric Explorer E. Most exciting is that one and the same instrument was operated during solar minimum and maximum conditions of the cycle 21. In this case the rather difficult problem of significantly changing calibration parameters with time has not yet occurred. One of the results indicates that the total EUV flux increased from July 1976 ($R_z = 0$; $F_{10.7} = 70$) to January 1979 ($F_{10.7} = 234$) by about a factor three (Hinteregger, 1981) as shown in Figure 11. The increase relative to the solar 'EUV minimum' (Hinteregger, 1977) is even larger, because the solar EUV flux during the rising solar cycle 21 was significantly higher than during the declining cycle 20 for similar solar conditions, as expressed by the classical indices R_z and $F_{10.7}$. Therefore, the long-term variability of the solar flux below 120 nm looks very different for both cycles.

4. Representation of Solar EUV Flux

There are periods for which correlation studies between the solar EUV flux and classical solar indices look promising in order to establish empirical relations to

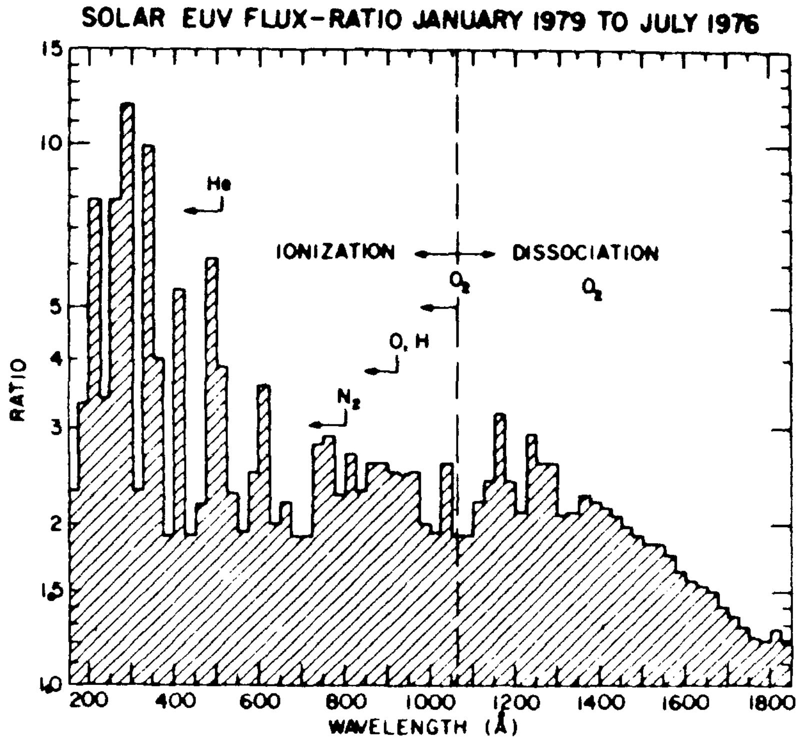

Fig. 11. Solar EUV flux increase from July 1976 to January 1979 (Hinteregger, 1981).

compute the solar EUV radiation from ground-based radio measurements. However, detailed analysis shows that this is only possible for certain periods with limited accuracy. Extrapolation to periods without actual EUV measurements may give misleading results (Hinteregger, 1976; Timothy, 1977; Schmidtke, 1978; Hinteregger, 1981).

The situation is quite different for the periods when the flux data were collected. There is a wealth of data for about 1100 different wavelengths including emission lines and continuum intervals. For some applications less detailed spectral information is needed. Then wavelength intervals can be combined to generate $EUV_{Y\text{-}Z}$ indices expressing the flux in units of $\mu W m^{-2}$ ($\text{merg}\, cm^{-2}\, s^{-1}$) with Y and Z representing the interval limits in nm (Schmidtke, 1976) or EUV_X for emission lines (X in nm). However, as more detailed information is required, as more numbers must be handled. For these cases another approach is studied (Hinteregger, 1981). Based on a computer stored reference spectrum of fluxes $F_{0\lambda}$ a variability index C_λ is assigned to each of 1957 different wavelengths in the wavelength range from 14–185 nm. In addition, the wavelengths are assigned to three 'variability classes' $K = 0$, 1, and 2, each of them being represented by one 'reference emission': $\lambda_0 = 177.5$–185 nm, $\lambda_1 = 58.43$ nm (He I), and $\lambda_2 = 33.54$ nm (Fe XVI). The relative flux value of a given day to the reference flux of this emission is denoted by R_K. If these three numbers R_0, R_1, and R_2 are known the corresponding total EUV flux F can be derived from

$$F = \sum_{\lambda} F_{0\lambda}(1 + (R_K - 1)C_\lambda).$$

The accuracy of this representation which depends on the validity of the parameters C_λ with respect to the length of the time periods (e.g. years or fractions of years) is still under study.

This system requires two tables ($F_{0\lambda}$ and C_λ) and three daily indices K_0, K_1, and K_2 to generate very detailed solar EUV fluxes. Figure 12 shows the variability of the 'reference emission' λ_1 for the period of AEROS B (Schmidtke *et al.*, 1981).

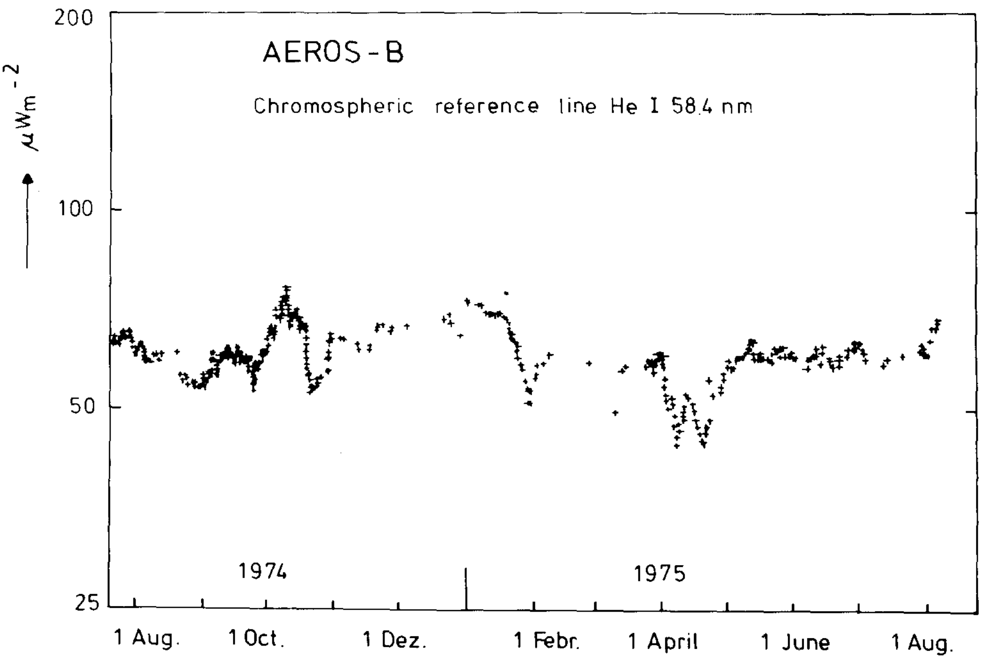

Fig. 12. Example for the variability of a 'reference emission' (Schmidtke, 1981).

5. EUV Flux as an Energy Source for the Upper Atmosphere

The EUV spectrometers as operated aboard the AEROS and Atmospheric Explorer satellites also measured quasi-height profiles of atomic oxygen in the 200–450 km altitude region during occultation. From these extinction measurements exospheric temperatures are derived. Analysing these data interesting longterm and medium-term trends are obtained: The decrease of the solar EUV flux by about 30% during the mission of AEROS-A is not reflected in the exospheric temperatures (Schmidtke *et al.*, 1981). The significant flux increase from 1974 to 1976 did not raise the exospheric temperatures significantly (Hinteregger, 1978), either. Also, flux variations with solar rotation do not control the exospheric temperatures significantly. Instead, the signatures of geomagnetic disturbances are much stronger. Two processes may cause this behaviour of the upper atmosphere:

(a) The solar wind is a competing energy source for the upper atmosphere (Schwenn, 1981). This can easily be traced for geomagnetic disturbances (Hinteregger, 1980; Schmidtke *et al.*, 1981).

(b) The heat efficiency of the solar EUV radiation in the upper atmosphere is not constant (Torr *et al.*, 1981).

Because of these effects and in view of the different types of variations the role of the solar EUV radiation as an energy source for the upper atmosphere is very difficult to describe.

6. Conclusions

The variability of the solar irradiance below 120 nm is strong and so time dependent that there is no substitute for direct measurements. The conversion of the EUV energy in the upper atmosphere is rather difficult to describe in view of the competing solar wind and the variable heat efficiency. The absolute accuracy of the EUV measurements should be increased by the application of true inflight calibration of the instruments as it is planned for Spacelab missions.

References

Delaboudiniere, J. P., Donelly, R. F., Hinteregger, H. E., Schmidtke, G., and Simon, P. C.: 1978, COSPAR Techniques Manual No. 7.
Detwiler, C. R., Purcell, J. D., and Tousey, R.: 1961, *Mem. Soc. Roy. Sci. Liège* **5**, Ser. IV, 254.
Elias, G. J.: 1923, *Tijdschr. Nederl. Radio Gen.* **2**, 1.
Freeman, F. F. and Jones, B. B.: 1970, *Solar Phys.* **15**, 288.
Hall, L. A. and Hinteregger, H. E.: 1970, *J. Geophys. Res.* **75**, 6959.
Heroux, L. and Higgins, J. E.: 1977, *J. Geophys. Res.* **82**, 3307.
Hinteregger, H. E.: 1961, *J. Geophys. Res.* **66**, 2367.
Hinteregger, H. E.: 1963, in C. de Jager (ed.), *The Solar Spectrum*, D. Reidel Publ. Co., Dordrecht, Holland, p. 179.
Hinteregger, H. E.: 1976, *J. Atmospheric Terrest. Phys.* **38**, 791.
Hinteregger, H. E.: 1977, *Geophys. Res. Letters* **4**, 231.
Hinteregger, H. E.: 1978, private communication.
Hinteregger, H. E.: 1980, private communication.
Hinteregger, H. E.: 1981, *Space Research* **XXI**, 39.
Hinteregger, H. E., Hall, L. A., and Schmidtke, G.: 1965, *Space Research* **V**, 1175.
Johnson, F. S., Malitson, H. H., Purcell, J. D., and Tousey, R.: 1958, *Astrophys. J.* **127**, 80.
Kiepenheuer, K. O.: 1945, *Ann. Astrophys.* **8**, 210.
Kreplin, R. W., Dere, K. P., Horan, D. M., and Meeking, J. F.: 1977, in O. White (ed.), *The Solar Output and its Variation*, Colorado Assoc. Univ. Press, Blouder, Colorado, p. 287.
Manson, J. E.: 1977, in O. White (ed.), *The Solar Output and its Variation*, Colorado Assoc. Univ. Press, Boulder, Colorado, p. 261.
Neupert, W. M., Behring, W. E., and Lindsay, J. C.: 1964, *Space Research* **IV**, 719.
Saha, N.: 1937, *Proc. Roy. Soc.* **A160**, 155.

Schmidtke, G.: 1976, *Geophys. Res. Letters* **3**, 573.
Schmidtke, G.: 1978, *Planetary Space Sci.* **26**, 347.
Schmidtke, G.: 1979a, *Daily Solar EUV Intensities obtained during the AEROS-A Mission*, Report IPW-W.B.11, Institut für Physikalische Weltraumforschung.
Schmidtke, G.: 1979b, *Space Research* **XIX**, 193.
Schmidtke, G., and Schweizer, W.: 1972, *Sonnenbeobachtung und -forschung mit Raketen*, Bundesforschungsbericht W 72-27, 31.
Schmidtke, G., Börsken, N., and Sünder, G.: 1981, *J. Geophys.* **49**, 146.
Schweizer W. and Schmidtke, G.: 1971, *Astrophys. J.* **169**, L27.
Schwenn, R.: 1981, *Space Research* **XXI**, 3.
Timothy, J. G.: 1977, in O. White (ed.), *The Solar Output and its Variations*, Colorado Assoc. Univ. Press, Boulder, Colorado, p. 237.
Timothy, A. F. and Timothy, J. G.: 1970, *J. Geophys. Res.* **75**, 6950.
Torr, M. R., Richards, P. G., and Torr, D. G.: 1981, *Space Research* **XXI**, 53.