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IRRADIATION SOLAR FLUX MEASUREMENTS BETWEEN 120 AND 400 NM. CURRENT POSITION AND FUTURE NEEDS*

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Abstract—The irradiation solar fluxes between 120 and 400 nm are reviewed and discussed. The disagreements between the recent observations are pointed out, emphasizing the future needs in this wavelength range for aeronomic purposes. Interpretation of the available data as function of the solar activity cannot explain their discrepancies, showing that the solar variability during the eleven-year cycle is still unknown.

1. INTRODUCTION

Ultraviolet solar irradiation in wavelengths ranging from 120 to 400 nm initiates the photochemistry of the neutral constituants of planetary atmospheres. For instance, photodissociation of molecular oxygen by radiation of wavelengths shorter than 242 nm is the initial source of odd oxygen in the terrestrial atmosphere, leading in particular to the formation of ozone by reaction with the molecular oxygen in the presence of a third body (N_2, O_2). On the other hand ozone is destroyed by photodissociation in the Hartley continuum and the Huggins bands by radiation at wavelengths shorter than 360 nm, producing the electronically excited atomic oxygen $O(^1D)$. These atoms are in fact the most important oxidizing agent in the stratosphere (Nicolet, 1975). An accurate knowledge of the solar irradiation flux at ultraviolet wavelengths and of its variations with the solar rotational period and the 11-year cycle is thereby fundamental in aeronomy.

The purpose of this work is to review the recent solar irradiance measurements between 120 and 400 nm. The discrepancies between the different observations will be pointed out and discussed in relation to the solar irradiation flux variability.

II. SOLAR IRRADIATION FLUX DATA

Ultraviolet solar radiation observations are generally focused on two different aspects: firstly, those concerning high spatial resolution and secondly, those regarding full disc measurements at medium resolution. Only the latter are fully pertinent for aeronomic purposes. Photochemical calculations require solar flux values averaged over a spectral range determined by the spectral structure of the absorption cross section of the atmospheric constituents. In most cases, wavelength intervals of 500 cm^{-1} and 1 nm are suitable in aeronomy and generally used. However, photodissociation rate coefficient calculations in the spectral range of the Schumann–Runge bands of molecular oxygen (175–204 nm) should be considered carefully. Generally, simple procedure based on the reduction factors can be performed for minor constituents with a smoothly varying absorption cross section by using solar irradiation fluxes averaged over 500 cm^{-1}, 1 nm, or for each band in the spectral range of the Schumann–Runge bands if the temperature effect is introduced. But this procedure cannot be applied directly, for instance, for nitric oxide whose absorption cross section reveals the presence of a rotational structure; such a case requires solar irradiance spectra with sufficient resolution. On the other hand, comparison between observational data obtained with different spectral resolutions ought to be made very carefully. Indeed peak intensities are very dependent on the equivalent slit width of the instrument pointed to the sun. Comparison at discrete wavelengths should, for this reason, be made for data with comparable spectral bandpasses. Generally, for spectral resolution of the order of 0.5 nm, the fine structure of the solar spectrum is sufficiently smeared to allow direct comparisons with less well resolved solar irradiance spectra. In

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addition, comparisons between measurements made on the whole disc and those made at the centre are not straightforward. This is due to the limb darkening occurring for wavelengths greater than 152 nm (Samain *et al.*, 1975). Beyond this limit, flux measurements made at the centre of the solar disk represent only an upper limit for the corresponding flux integrated over the whole solar disc. It is for this reason that measurements made on radiation originating in a relatively small area of the sun have been excluded from this work.

A correct interpretation of the available data must take into account the flux variabilities arising from changes in solar activity. These belong to three categories determined by their time scale: firstly, variations related to flares having a very short life time; secondly, those related to the solar rotation period (27-days) and finally, those related to the 11-year cycle. The solar irradiation flux enhancement due to the flares could be considered as negligeable for wavelengths greater than 140 nm, according to Heath (1969) who observed a 3B flare on 21 April, 1969 by means of broadband sensors centred around 120, 180 and 260 nm. For this flare he reported an enhancement of 16% for the Lyman α emission line and no measurable effect (less than 1%) for the other wavelength ranges. This result is, in fact, confirmed by the flare observations made by Hall (1971).

Since the solar irradiance enhancement related to solar flares seems to be negligeable even for the Lyman α line and since there is a lack of data between 120 and 400 nm on possible variations due to a flare, only solar variability related to the 27-day period and the 11-year cycle will be considered in this work.

II.I. 120–175 *nm wavelength range*

The solar irradiation of this wavelength range is mainly absorbed in the lower thermosphere by the molecular oxygen, except for the solar Lyman α emission line which penetrates deeply into the mesosphere, leading to the formation of the ionospheric *D* region.

The Lyman α line of hydrogen emitted by the Sun is the most intense chromospheric emission line in the solar spectrum. Its irradiation flux corresponds to the total energy emitted by the Sun for wavelengths below 150 nm. Its absolute intensity was first measured in 1949 by Friedman *et al.* (1951). Since that time, roughly 40 measurements have been performed using different techniques (see the recent review-paper by Vidal-Madjar, 1977). Most of the experimenters have quoted a measurement accuracy of the order of ±30%. The generally accepted mean integrated value is $3\times 10^{11}\ h\nu\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$. However, this value varies with the 11-year cycle and with the solar rotational period. The most recent observations of the variation related to the 27-day solar rotation are in good agreement and suggest a 30% maximum variability (Hall and Hinteregger, 1970; Heath, 1973; Woodgate *et al.* 1973 and Vidal-Madjar, 1975); Prag and Morse results (1970) gave a 60% variability but referred to only one solar rotation. It should be pointed out that the variation due to the solar rotation is of the order of the absolute accuracy claimed by the different authors. On the other hand, some absolute measurements carried out at the same time disagree by an important factor reaching, for instance, 70% for two observations performed on 7 March 1970 by Smith (1972) and Dickinson (1972); any conclusion concerning the Lyman α variability must, therefore, be very speculative.

In addition, any series of long-term observations generally suffers from aging in the sensitivity of the instrument; satellite-borne instruments need to be recalibrated during the observational period by rocket-borne experiments.

These fundamental remarks are equally valid for the variability measurements over the 11-year solar cycle. The most recent study based on the OSO 5 data (Vidal-Madjar, 1975), which represent the longest survey of Lyman α irradiation flux with only 10% of instrumental sensitivity degradation per year, leads to a variability of the order of 40%. This value is in good agreement with both the 30% variability proposed by Weeks (1967) and the inter-comparison of measurements performed during the solar cycle 20 as presented in Fig. 1.

In the spectral range 120–175 nm, the first measurements fully relevant for aeronomic purposes were those published by Detwiler *et al.* (1961). By using a photographic detection technique, the accuracy of the data was estimated to be better than ±20%. Nevertheless, keeping in mind the restriction concerning radiance measurements at the centre of the solar disc, 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 centred 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

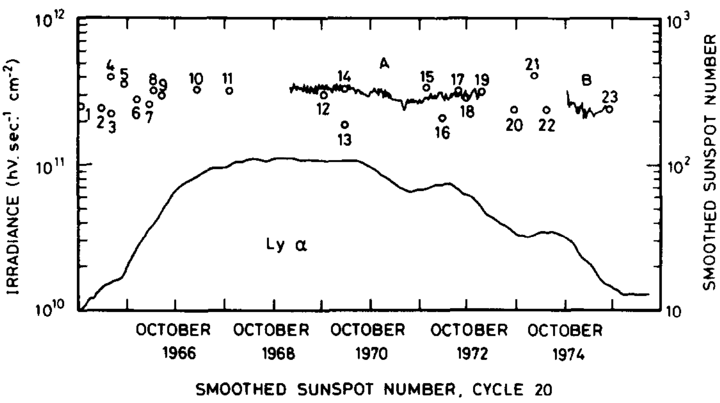

FIG. 1. COMPARISON OF LYMAN α SOLAR IRRADIATION FLUX MEASUREMENTS DURING THE SOLAR CYCLE 20. THE SMOOTHED SUNSPOT NUMBERS ARE ALSO SHOWN.

References: (1–6 and 9), weeks (1967); (7) Fossi *et al.* (1968); (8) Bruner and Parker (1969); (10) Hinteregger (1970); (11) Bruner (private communication); (12) woodgate *et al.* (1973); (13) Smith (1972); (14) Dickinson (1972); (15) Huggins (1976); (16) Ackerman and Simon (1973); (17) Prinz (1974); (18) Heroux *et al.* (1974); (19 and 20) Rottman (1974); (21) Oshio (private communication); (22) Heroux (private communication); (23) Rottman (private communication); (A) Vidal-Madjar (1975); (B) Vidal-Madjar (private communication) (after Delaboudinière *et al.*, 1978).

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. More recently, new 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, characterized by an accuracy of respectively ±15% and ±20%, also used a photoelectric detector. Samain and Simon (1976) deduced the solar irradiance from photographic stigmatic spectra, by measuring the radiance at the

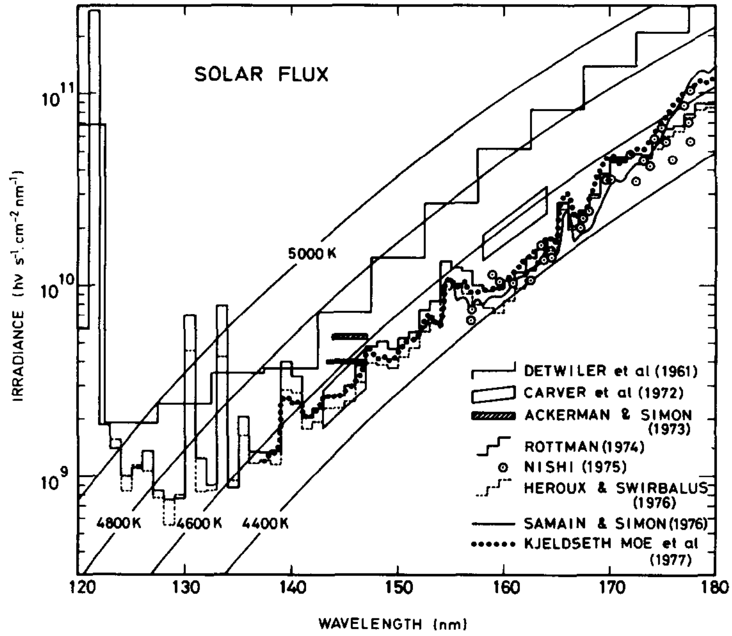

FIG. 2. COMPARISON OF U.V. SOLAR FLUX REPORTED BY VARIOUS EXPERIMENTERS FROM 120 TO 180 nm. FLUXES FOR DIFFERENT BLACKBODY TEMPERATURES ARE ALSO SHOWN.

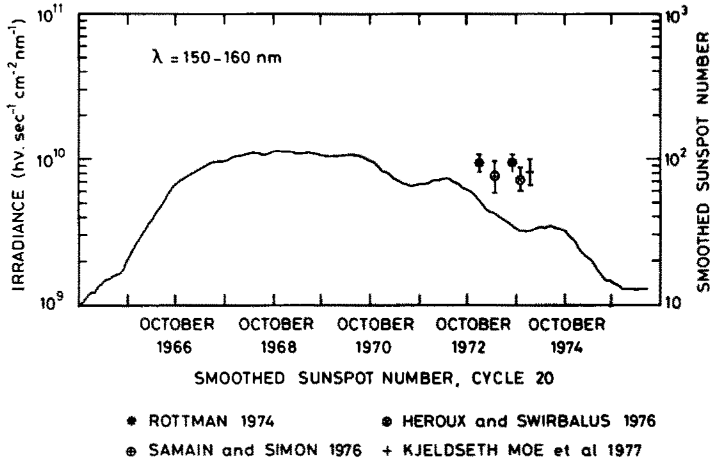

FIG. 3. COMPARISON OF SOLAR IRRADIATION FLUX MEASUREMENT IN THE 150–160 nm INTERVAL DURING THE SOLAR CYCLE 20. THE SMOOTHED SUNSPOT NUMBERS ARE ALSO SHOWN (AFTER DELABOUDINIERE *et al.*, 1978).

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 and an absolute accuracy of 30%. Very recently, Kjeldseth Moe *et al.* (1978) have 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). They quoted an accuracy of ±25%. All these data are reported in Fig. 2 for comparison. Discrepancies 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 α irradiance variations could not exceed 30% as mentioned above. Beyond 160 nm the agreement between all the measurement 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.

Discrepancies of the order of 40% seem difficult to relate to the solar variability with the 11-year cycle because of the lack of data covering a sufficiently large period of the solar cycle as shown in Fig. 3. On the other hand a more complete study of the irradiance variations due to the solar rotation was made very recently by Hinteregger *et al.* (1977) by means of the AE satellites. The strongest variations observed during the Carrington rotation No. 1615 (June 1974) are reported on Fig. 4 and compared with the previous data published by Heath (1973), showing a maximum variability of 25 and 9% at 155 and 170 nm respectively. However, it must be pointed out that such solar variations are, in fact, of the same order of magnitude as both the measurement differences and their accuracy ranges.

II.2. 175–240 *nm wavelength interval*

Solar irradiation fluxes in this wavelength interval are very important for stratospheric and

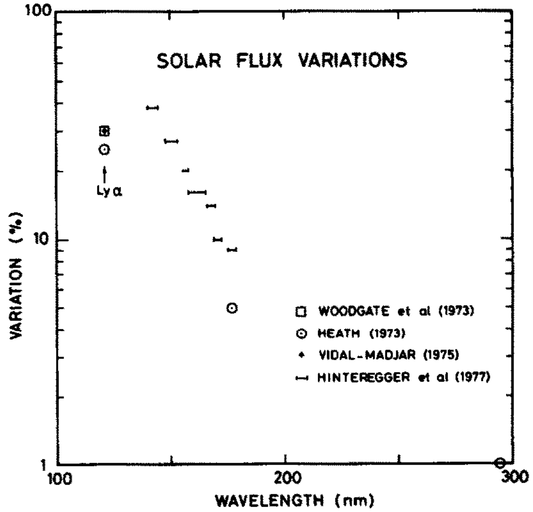

FIG. 4. SOLAR FLUX VARIATIONS RELATED TO THE SOLAR ROTATIONAL PERIOD FROM LYMAN α TO 300 nm. THE VALUES OF HINTEREGGER *et al.* (1977) CORRESPOND TO THE CARRINGTON ROTATION NO. 1615 (JUNE 1974).

mesospheric aeronomy. They are mainly responsible for the photodissociation of molecular oxygen below 90 km which absorbs radiation of wavelength shorter than 242 nm. Some minor constituents such as nitrogen oxides, water vapor and halocarbons also undergo photodissociation in this wavelength range. Unfortunately, the solar spectrum is not sufficiently well known especially between 175 and 204 nm corresponding to the Schumann–Runge band system. With the exception of the data of Detwiler *et al.* (1961) already discussed, the only measurements covering this wavelength range are those deduced very recently by Samain and Simon (1976), already mentioned, and those of Brueckner *et al.* (1976) who also determined the solar irradiance fluxes 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. The data, extending up to 210 nm were integrated over 1 nm interval for comparison and are reported on Fig. 5 with the other measurements covering partially the same wavelength range. Figure 6 illustrates the ratio between all the recent observations taking as reference the values of Samain and Simon (1976). The first conclusion to be drawn is that the data of Brueckner *et al.* (1976) are quasi systematically 25% lower than those of Samain and Simon (1976). A good agreement accurs at 175 nm with the results of Rottman (1974) and of Heroux and Swirbalus (1975), but discrepancies of the order of 50% appears around 190 nm. Such a difference has been discussed by Samain and Simon (1976) who come to the conclusion that, from 180 to 194 nm, their own data should be considered as an upper limit for the solar irradiance while those of Heroux and Swirbalus should give a lower limit. Beyond 200 nm, the most recent irradiance measurements are those obtained by Simon (1974) with a balloon borne spectrometer. They are 40% lower than the previous balloon measurements reported by Ackerman *et al.* (1971) and are also lower than Broadfoot's results (1972), except between 226 and 230 nm where the agreement is within 15%. The observations of Broadfoot (1972) were obtained by means of a rocket borne spectrometer with a spectral resolution of 0.3 nm.

The accuracies quoted by these experimenters fall in the range ±10 to ±30% for all the measurements mentioned above. For this wavelength interval, the evidence for variability during the solar cycle 20 is no more conclusive than at the shorter wavelengths. This fact is illustrated by Fig. 7 where the available data at 200 nm are plotted as a function of the dates of the measurements and compared with the smoothed Sunspot number during

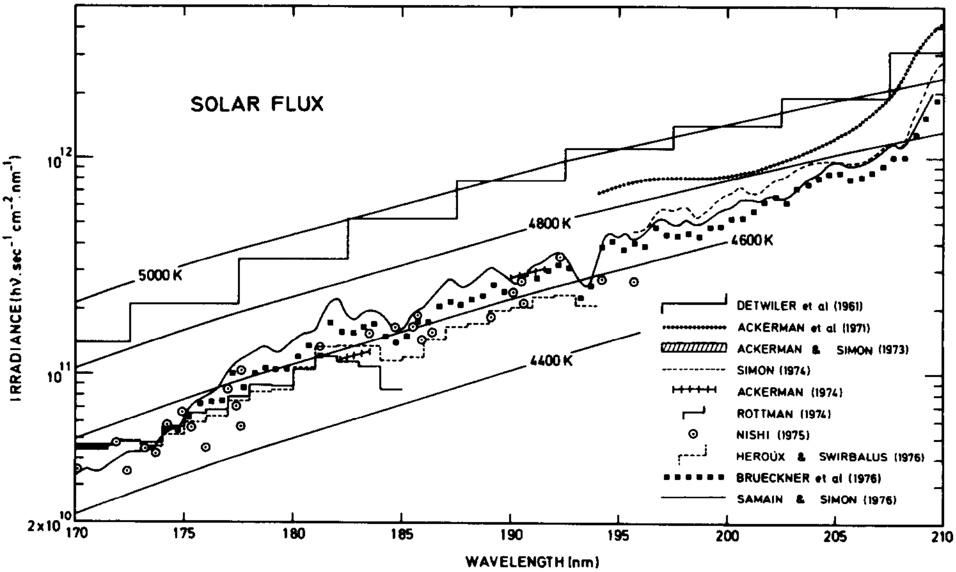

Fig. 5. Comparison of u.v. solar flux reported by various experimenters from 170 to 210 nm. Fluxes for different blackbody temperatures are also shown.

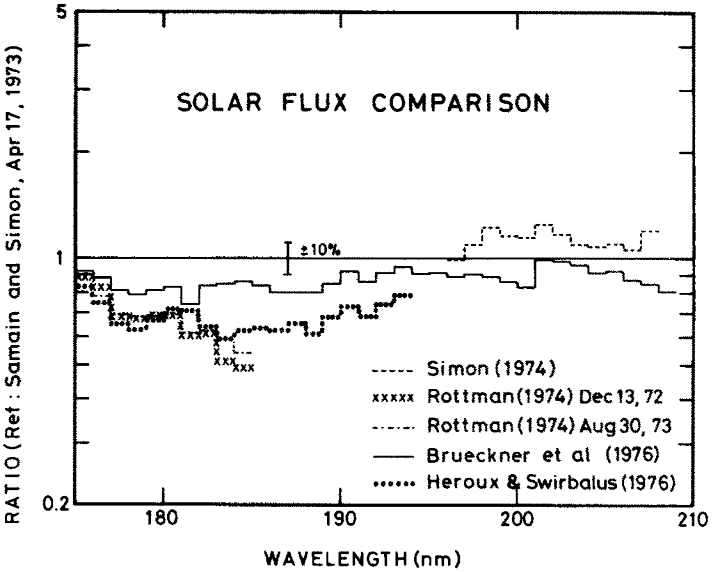

FIG. 6. RATIO OF SOLAR IRRADIATION FLUX MEASUREMENTS FROM 175 TO 210 nm IN COMPARISON WITH THE DATA OF SAMAIN AND SIMON (1976).

solar cycle 20. Figure 8 compares the data at 177, 200 and 220 nm with the 10.7 cm flux as a reference state. The lack of reliable data is quite evident and it is impossible to reach any unambiguous conclusion; moreover, the omission of one or two results could lead to opposite conclusions. It should be mentioned that Heath (1976), on the basis of only his own measurements performed by satellites and by rockets since 1966, claimed that the solar irradiance at 200 nm should vary by a factor of two. This statement is in contradiction with a more complete analysis of the data and with the variability of the Lyman α chromospheric line which could not exceed 40–60% during solar cycle 20.

The irradiance variations related to the solar rotation are less than 10% beyond 175 nm and are decreasing with increasing wavelength (Fig. 5). The results of Heath (1973) and Hinteregger *et al.* (1977) were also confirmed by an analysis based on the plage radiance measurement carried out by Brueckner *et al.* (1976). Such variability is comparable to that due to the Sun–Earth annual distance change involving periodic solar variation of 6.6% from January (max.) to July (min.).

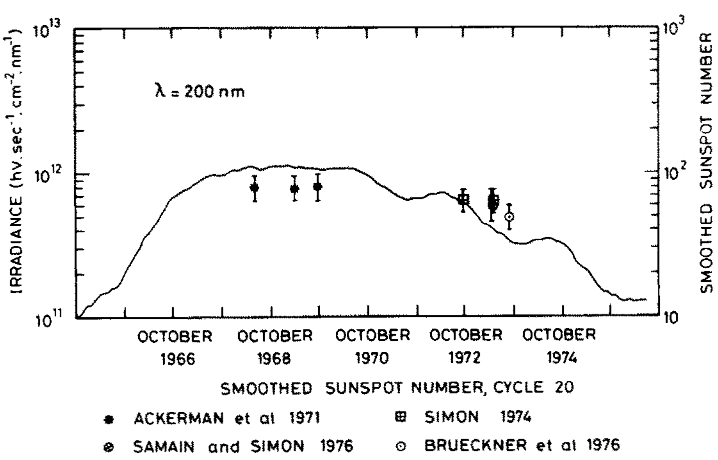

FIG. 7. COMPARISON OF SOLAR IRRADIATION FLUX MEASUREMENTS AT 200 nm DURING THE SOLAR CYCLE 20. THE SMOOTHED SUNSPOT NUMBERS ARE ALSO SHOWN (AFTER DELABOUDINIERE *et al.*, 1978).

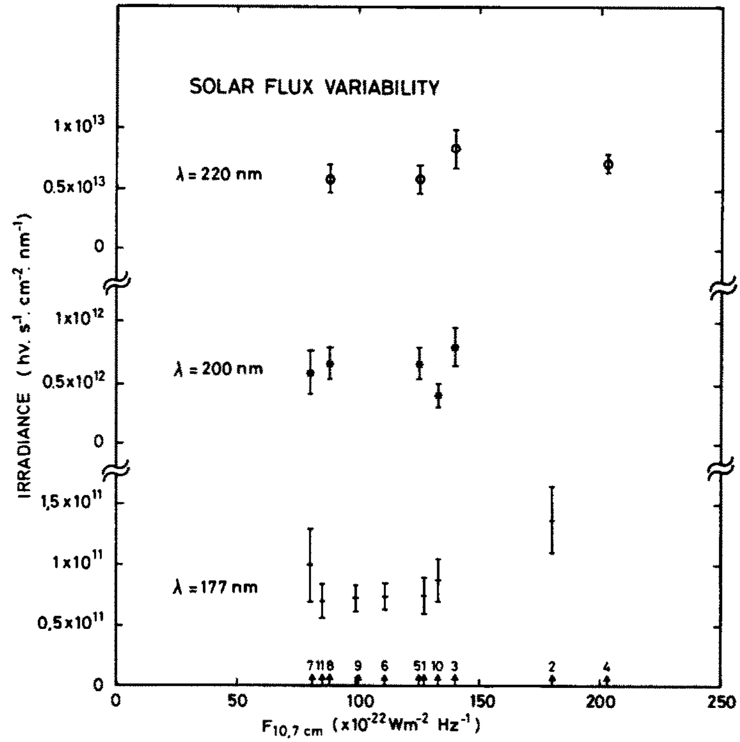

Fig. 8. Solar flux variability at 177, 200 and 220 nm in function of the 10.7 cm solar flux. References: (1 and 2) Heath (1976); (3) Ackerman *et al.* (1971); (5 and 6) Simon (1974); (6 and 9) Rottman (1974); (7) Samain and Simon (1976); (10) Brueckner *et al.* (1976); (11) Heroux and Swirbalus (1976).

II.3. 240–400nm *wavelength interval*

This wavelength range is directly related to the photodissociation processes in the stratosphere and in the troposphere. The recent published solar irradiance values are based on satellite, rocket, balloon, aircraft and ground-based observations. The only measurements performed by satellite were published by Heath (1973) reporting irradiance values at 10 discrete wavelengths between 250 and 350 nm. The rocket measurements of Broadfoot already mentioned from 210 to 320 nm are the most reliable contribution covering continuously the most important wavelength range for the photodissociation of ozone (Fig. 9). On the other hand, Arvesen *et al.* (1969) carried out from aircraft measurements from 300 to 2500 nm by means of a double spectroradiometer having a resolution of 0.1 nm in the u.v. Unfortunately, they have some discrepancies with Broadfoot's data between 300 and 320 nm in which occurs the limit of photodissociation of O_3 producing the excited atomic oxygen $O(^1D)$ which is particularly important for the stratospheric aeronomy (Nicolet, 1975). The values of Simon (1975) extending from 284 to 354 nm obtained by balloon observations are in very good agreement with those of Broadfoot (1972) up to 300 nm and with those of Arvesen *et al.* (1969) beyond 330 nm (Fig. 10). In fact, Broadfoot (1972) claimed an accuracy of ±10% for his measurements except beyond 300 nm where the error is larger. On the other hand Arvesen *et al.* (1969) estimate their error to be 25% at 300 nm, 6% at 320 nm and 3.2% at 400 nm. The data of Simon (1975) could therefore provide useful irradiance values between 300 and 330 nm. Other measurements obtained from aircraft are those of Thekaekara (1969) but the tables of irradiances integrated over 5 nm are based on an average of data coming from four different instruments. More recently, irradiances at 0.1 nm intervals were published by Thekaekara (1974) in the wavelength range 300–610 nm. Unfortunately, his results show many errors in the wavelength scale (Simon, 1975) making difficult a correct comparison with the other measurements. Observations of De Luisi (1975) from

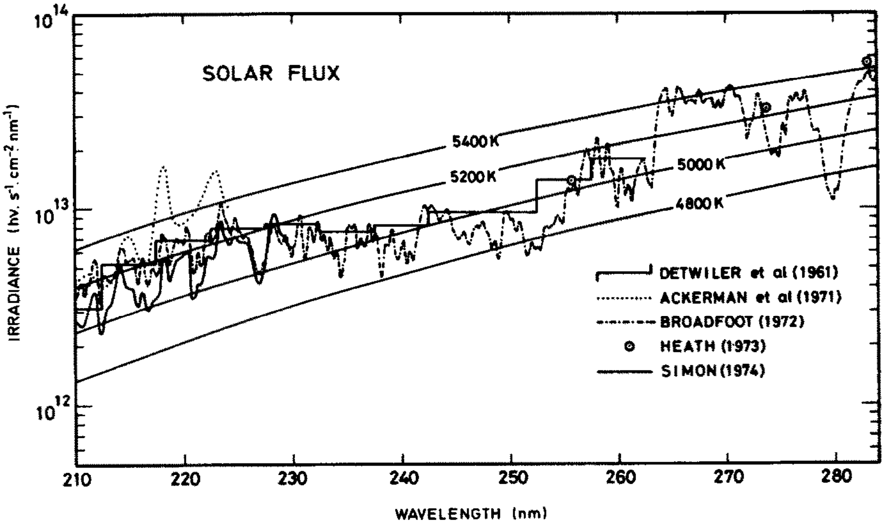

FIG. 9. COMPARISON OF U.V. SOLAR FLUX REPORTED BY VARIOUS EXPERIMENTERS FROM 210 TO 280 nm. FLUXES FOR DIFFERENT BLACKBODY TEMPERATURES ARE ALSO SHOWN.

298.1 to 400 nm were obtained from ground-based measurements but only relative calibration of the spectrometer was performed. Absolute irradiation fluxes were obtained adjusting the total energy in the wavelength range 300–400 nm on the standard solar spectral irradiance curve published by Thekaekara (1970). On the other hand, Labs and Neckel (1970) measured, from a high mountain observatory, the solar radiance near the disc centre and computed the irradiation fluxes from 330 to 1250 nm integrated over 10 nm, using the limb-darkening data of David and Elste (1962). The accuracy of all these observations allows an estimation of the solar irradiance flux within 10% around 300 nm and within 5% around 400 nm.

The irradiance variability is as poorly known in this wavelength range as below 200 nm. As for 200 nm, Heath (1976) also made measurement at

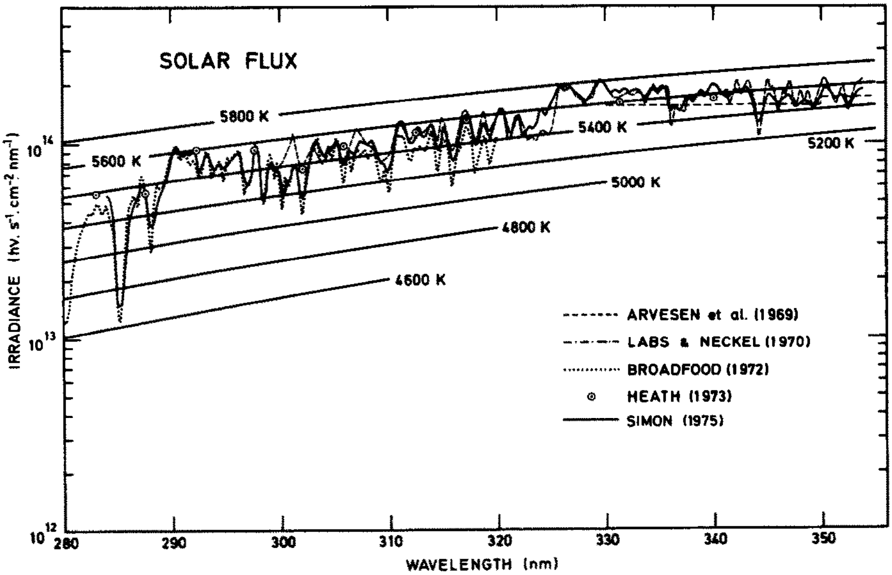

FIG. 10. COMPARISON OF U.V. SOLAR FLUX REPORTED BY VARIOUS EXPERIMENTERS FROM 280 TO 350 nm. FLUXES FOR DIFFERENT BLACKBODY TEMPERATURES ARE ALSO SHOWN.

300 nm leading to a variability related to the 11-year cycle of the order of 20%. Nevertheless, taking into account the other irradiance measurements, there is no conclusive evidence for such variability. The irradiance variations due to the solar rotational period are less than 1% beyond 300 nm according to Heath (1973).

III. CONCLUSIONS AND FUTURE NEEDS

Accuracy in the field of ultraviolet spectroradiometry of the Sun depends upon many factors which can be divided into three parts: (a) the uncertainty of the available radiometric primary and transfert standards, (b) the lack of precision in the instrument calibration in the laboratory, (c) the errors introduced by the measurements of the Sun itself.

The spectral irradiance transfer detector standards available from the National Bureau of Standards have now an uncertainty quoted from 5 to 10% for the photodiode working in the 115–254 nm interval, and of 5% for the silicon photovoltaic detectors working beyond 257 nm. The transfer source standards give an uncertainty between 3 and 6% respectively for the tungsten-halogen source beyond 250 nm and for the deuterium lamp from 200 to 350 nm. In addition, synchrotron irradiation flux can also be used for ultraviolet calibration with an uncertainty of 5%. Such values are generally smaller than the quoted accuracies for the available solar irradiance measurements which have to take into account all the errors introduced by the spectroradiometric measurement, including some instrument definition factors but also and mainly the fact that solar ultraviolet observations require space observations. This means that the measurements are made at a relatively long time after the laboratory calibration, that the instruments generally suffer from contamination and consequently show a loss of sensitivity which is especially evident for the free-flyer instruments. Table 1 summarizes the quoted accuracies and the discrepancies already discussed in this work.

The discrepancies are still too large to allow an unambiguous interpretation of solar variability; no conclusion concerning its magnitude can be drawn because of the error associated with all the measurements and of the inadequate time coverage during the solar cycle 20.

The first and most urgent requirement for the solution of the question of the solar ultraviolet irradiance variability is certainly the improvment of the measurement accuracy by means of, for instance, the "Spacelab" allowing some absolute calibration experiment in the space environment of solar observational instrument which can, in addition be recalibrated after the flight. One example of such experiment has already been proposed by Schmidtke (1976) for the EUV range. The second requirement is to survey continuously the solar irradiance using free-flyer instruments which should be cross-calibrated regularly by means of shuttle-borne instrument. In addition, some intercomparisons of instrument calibration would be very useful to meet the requirements concerning the reproductibility of the solar irradiance measurements. These

TABLE 1.

	Ionosphere thermosphere higher mesosphere	Lower thermosphere	Mesosphere higher stratosphere	Stratosphere troposphere
Wavelength Interval (nm)	Ly α(121,6)	120–175	175–240	240–400
Quoted accuracy	±30%	±15 to ±30%	±10 to ±30%	±5 to ±10%
Discrepancy	100%	40%	40–25%	1 measurement from 230 to 285 nm
Required accuracy	5%	5%	5%	5% absolute 1–0.1% relative
Required spectral resolution		1–5 nm	0.1–1 nm (0.003 nm from 175 to 204 nm)	0.1–1 nm (0.01 nm for occultation measurement)
Variability (27-day)	30%	30–10%	10–1%	<1%
Variability (11-year)	40–60%	100%	100%	50–20%?

accuracy requirements are also summarized in Table 1. Strong emphasis is generally placed on the need to improve the accuracy of measurement of the solar irradiation flux and its possible variations, as they affect to the stratospheric aeronomy, in order to reach a better understanding of the middle atmosphere.

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