SOLAR FLUX DETERMINATION IN THE SPECTRAL RANGE 150–210 nm

DENYS SAMAIN
Laboratoire de Physique Stellaire et Planétaire, B.P. 10, F-91370 Verrières le Buisson, France

and

PAUL C. SIMON
Institut d'Aéronomie Spatiale de Belgique B-1180, Brussels, Belgium

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Abstract. Solar irradiation fluxes are determined between 150 and 210 nm from stigmatic spectra of the Sun obtained by means of a rocket-borne spectrograph. Absolute intensities at the disk center with a spectral resolution of 0.04 nm and a spatial resolution of 7 arc sec are presented. From center-to-limb intensity variations determined from the same spectra, mean full disk intensities of the quiet Sun can be deduced. In order to compare them with other measurements, the new solar fluxes have been averaged over a bandpass of 1 nm.

1. Introduction

The photodissociation of molecular oxygen by the ultraviolet solar irradiation flux ranging from 175 to 242 nm is the initial source of odd oxygen in the mesosphere and the stratosphere. This wavelength interval corresponds to the Schumann–Runge band system (204–175 nm) and to the Herzberg continuum (242–204 nm) of molecular oxygen. In this spectral region, solar fluxes are not sufficiently well known, especially between 180 and 200 nm. The first complete measurements reported by Detwiler *et al.* (1961) are generally considered as being too high by an important factor. The other flux values covering also this whole spectral region which were published by Widing *et al.* (1970) correspond to values measured at the center of the solar disk and cannot be used in aeronomy which requires total disk solar flux values. The most recent measurements have been obtained by means of rocket-borne spectrometers by Rottman (1974) between 116 and 185 nm and by Heroux and Swirbalus (1976) between 125 and 194 nm. In addition, Brueckner *et al.* (1976) have deduced average disk intensities from a quiet Sun spectrum between 175 and 210 nm. Other measurements have also been obtained by Simon (1974) by means of a balloon-borne spectrometer between 196 and 230 nm. Rocket measurements agree very well together below 180 nm leading to an equivalent blackbody solar temperature of the order of 4550 K in this spectral region. Simon's data lead to a brightness temperature of the Sun of the order of 4700 K at 196 nm. There is therefore an important increase in the solar flux between 180 and 196 nm which must be determined to calculate accurate photodissociation rate coefficients of minor stratospheric con-

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stituents (Kockarts, 1976). Data published by Heroux and Swirbalus (1976) and by Brueckner *et al.* (1976) do not solve completely this problem, since systematic differences of roughly 40% can be seen between these observations. Furthermore, high spectral resolution fluxes are needed, to calculate, for example, the photodissociation rate coefficient of nitric oxide which has absorption bands with rotational structure in the Schuman–Runge region (Cieslik and Nicolet, 1973).

The purpose of this work is to determine the solar irradiation fluxes between 150 and 210 nm from stigmatic spectra of the Sun obtained by Samain *et al.* (1975), by computing the mean flux over the whole disk from the center-to-limb variations determined from the same spectra.

2. Observational Data and Calibration

The stigmatic spectra of the Sun between 120 and 210 nm were obtained during a rocket flight, April 17, 1973, by means of a double Wadsworth mounting spectrograph. This experiment leads to the determination of solar disk intensities with a spectral resolution of 0.04 nm and to center- to-limb distributions with spatial resolution of 7 arc sec. Absolute intensities at the center of the disk have

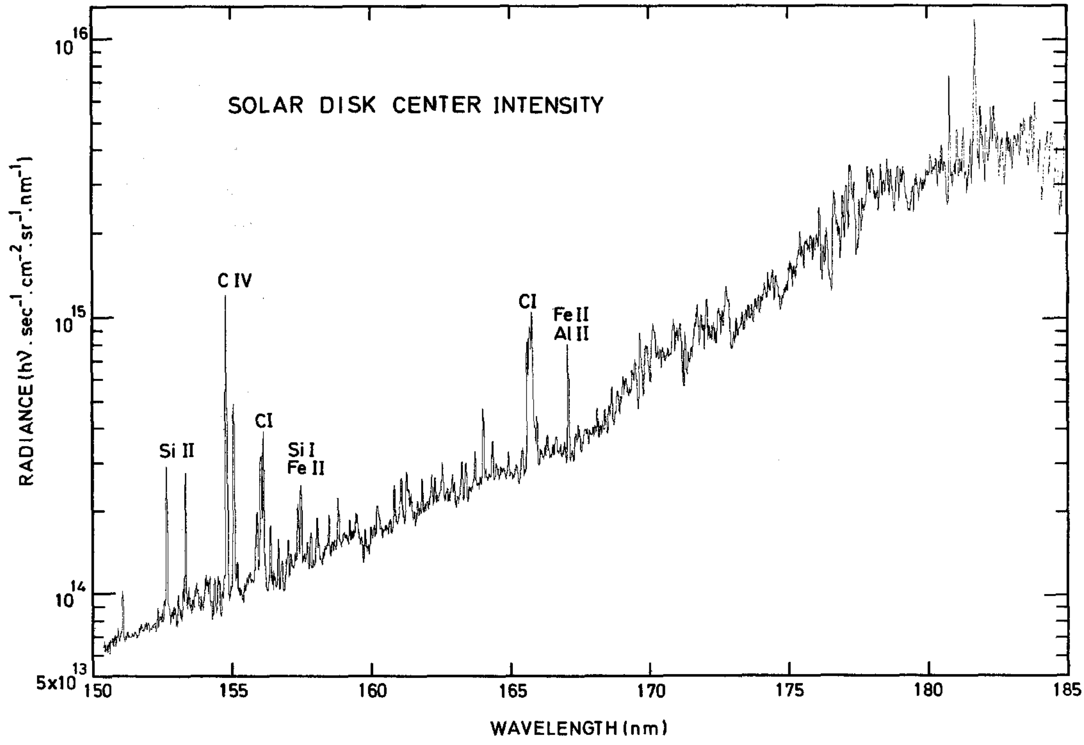

Fig. 1. Absolute intensities for the solar disk center between 150 and 185 nm with a spectral resolution of 0.04 nm and a spatial resolution of 7 arc sec.

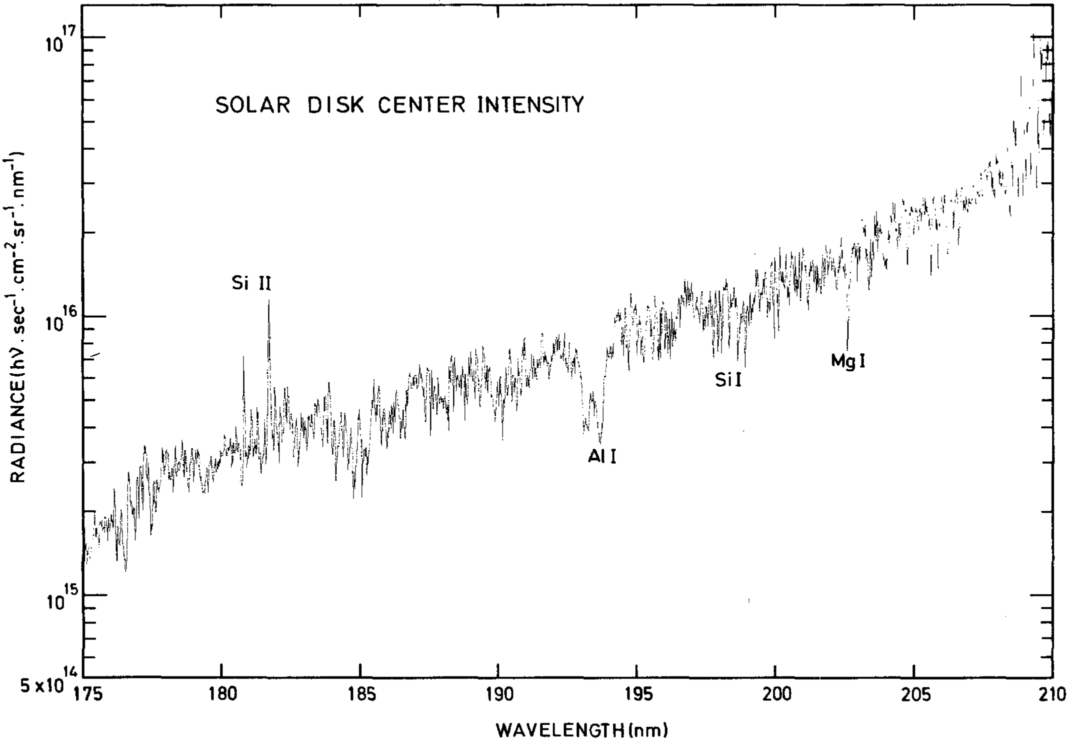

Fig. 2. Absolute intensities for the solar disk center between 175 and 210 nm with a spectral resolution of 0.04 nm and a spatial resolution of 7 arc sec.

been published by Samain *et al.* (1975). For wavelengths below 168 nm, values reported in their Figure 9 correspond to minima of the spectrum while beyond this wavelength they correspond only to continuum peak intensities, excluding emission lines. Comparison with other measurements cannot be made directly since the spectral resolution of the instrument plays an important role in the measured intensities. In the spectral range 150–210 nm, differences of ±20% from the highly resolved intensities can occur when the measurements are smeared by a triangular function of 1 nm half width. This fact could explain the equivalent blackbody temperature of the Sun of nearly 4900 K at 200 nm.

The absolute calibration of the instrument which is described by Samain *et al.* (1975) was carried out at the Culham Laboratory (Abingdon, England) using standard detectors calibrated against ionization chambers as absolute standards (Burton *et al.*, 1973). The film absolute sensitivity was measured at 120, 130, 149, 164, 174, 202 and 206 nm. The instrumental transmission was determined at the same wavelength, except at 164 and 202 nm. This determination is based on measurements made at the instrument aperture of a calibrated light which is related to film densities by means of the film characteristic curve. Moreover, by another experimental method, the instrument sensitivity was determined every

5 nm between 120 and 190 nm. The instrumental response was also measured as a function of wavelength along the spectrograph slit. The average instrumental sensitivity curve is shown in Figure 3 by Samain *et al.* (1975). Intensity calculations from the film optical densities are based on the relative characteristic curves of the film obtained from inflight calibration spectra and on absolute sensitivity curves obtained by interpolating between values measured at the aforementioned wavelengths. Except below 155 nm, only densities between 0.3 and 1.3 have been considered in our work. Figures 1 and 2 show the solar intensities measured at the disk center.

3. Center-to-Limb Variations

The center-to-limb intensity variations which were initially determined in a bandpass of 0.05 nm of the solar continuum from the stigmatic spectra at 25 wavelengths (Samain *et al.*, 1975) have been extended between 146 and 210 nm in order to determine accurately mean full disk intensities of the quiet Sun versus wavelength each 1 or 2 nm whenever possible. The mean intensity $\bar{I}(\lambda)$ integrated over the whole disk can be deduced from the variation of the solar intensity $I(\mu, \lambda)$ from the center ($\mu = 1$) to the limb ($\mu = 0$) through the relation:

$$\bar{I}(\lambda) = 2\int_0^1 \mu I(\mu, \lambda)\,\mathrm{d}\mu.$$

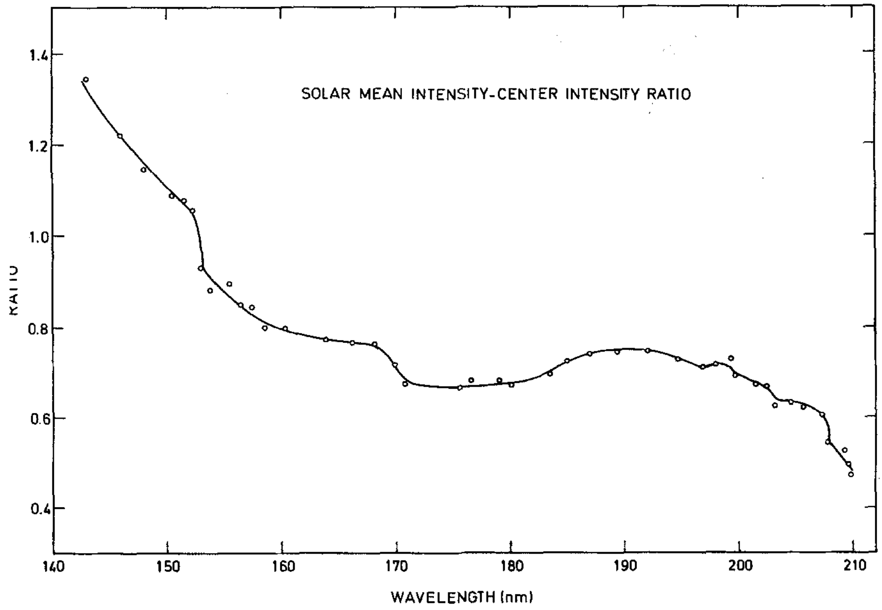

Fig. 3. Ratios between mean full disk intensities and specific intensities at the center of the Sun versus wavelength. Only data points corresponding to the continuum have been plotted.

Ratios between mean solar intensities $\bar{I}(\lambda)$ and specific intensities at the center of the disk $I(0, \lambda)$ have been calculated for many wavelengths and are shown in Figure 3, where each point corresponding to the continuum is an average over 6 observed values in most cases. The error on $\bar{I}(\lambda)/I(0,\lambda)$ is deduced from the errors on the center-to-limb intensity variations and has been estimated to be of the order of 6 to 8% between 150 and 210 nm and larger than 10% below 150 nm.

An analysis has also been undertaken for several absorption and emission lines of the solar spectrum in order to determine their influence on the mean intensity integrated over 1 nm. Since weak lines are generally narrow in comparison with the spectrograph resolution, the center-to-limb measurements lead to the same values as those deduced for the nearby continuum. For broader or stronger lines, the center-to-limb variations are different from continuum values but their differences are much less important than the possible error in the absolute intensity measurements. Limb darkening is weaker in absorption lines than in the continuum, while limb brightening is more intense in emission lines. For both cases, the effect of smearing is to increase the average level of the mean intensity and thereby the level of the solar flux. If the detailed structure of the spectral intensity may be slightly modified at a few wavelengths, this effect is generally less than 3% and negligeable when irradiation flux values are averaged over a spectral range of 1 nm. However, special care has been taken for the very broad autoionization lines of aluminum at 193.2 and 193.6 nm, and for lines with intense emission or very large limb-brightening such as the lines of C IV at 154.82 and 155.08 nm, Si I/Fe II at 157.49 nm, Fe II/He II at 164.02 nm, C I at 165.7 nm and Si II at 181.69 nm for which differences vary between 4 and 12%. The solar fluxes for intervals of 1 nm which include these lines have been corrected consequently by introducing the correct center-to-limb variation in the calculations.

4. Results and Discussion

Full disk solar irradiation fluxes deduced between 150 and 210 nm from the intensities at the center of the disk and from the center-to-limb intensity variations have been integrated over a spectral range of 1 nm (Figures 4 and 5). Table I which gives also the flux values for 1 nm intervals in photons s^{-1} cm^{-2} nm^{-1} and in mW m^{-2} nm^{-1}, allows a direct comparison with other published values. A good agreement with data reported by Rottman (1974) and Heroux and Swirbalus (1976) is obtained around 160 nm and at 175 nm, and with values deduced by Brueckner *et al.* (1976) over their whole wavelength range (175–210 nm). For wavelengths greater than 180 nm our mean values are roughly 50% higher than those published by Heroux and Swirbalus (1976). Nevertheless, they are not different from the recent measurements of Simon (1974) around 200 nm which were obtained in the stratosphere near 40 km of altitude by means of a balloon-borne spectrometer and a photoelectric detector with a spectral bandpass of 0.6 nm.

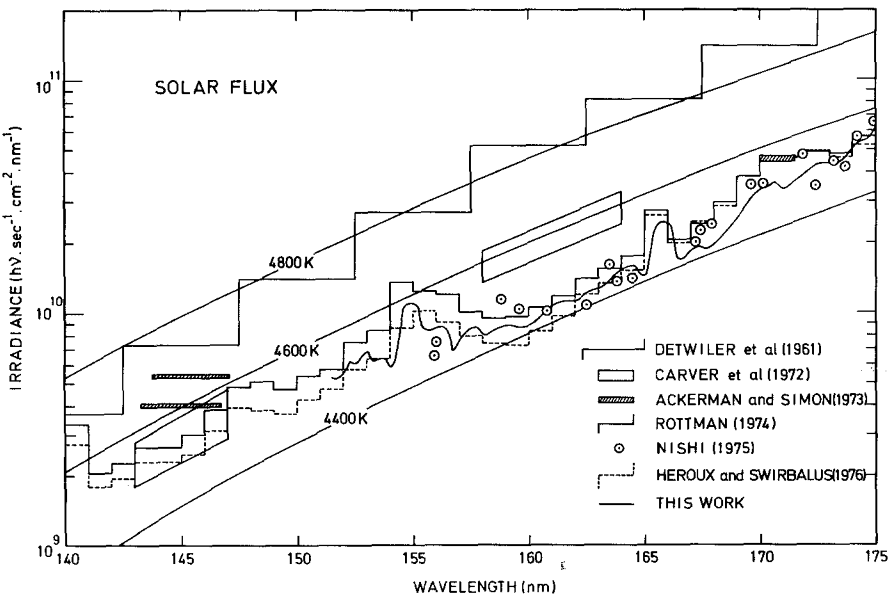

Fig. 4. Comparison of the present solar irradiation flux determination integrated over 1 nm with various flux measurements from 140 to 175 nm and with different curves of the blackbody temperatures.

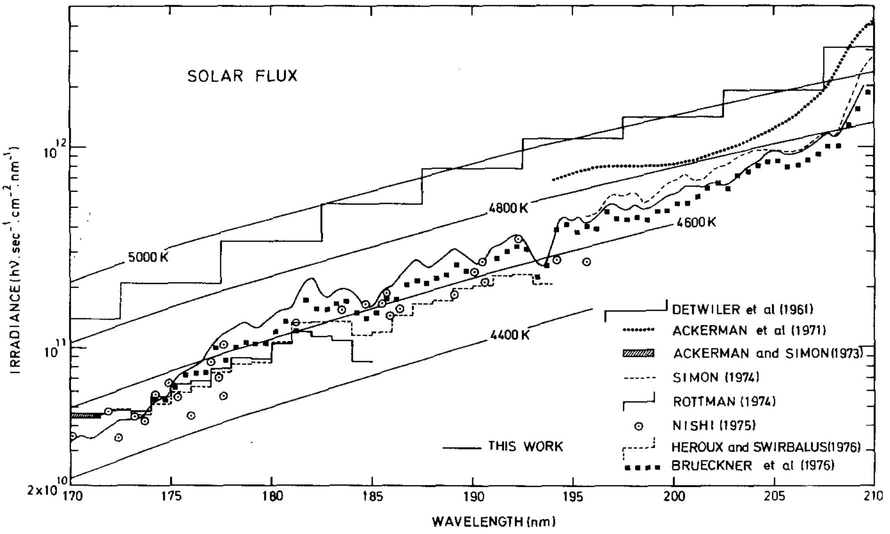

Fig. 5. Comparison of the present solar irradiation flux determination integrated over 1 nm with various flux measurements from 170 to 210 nm and with different curves of the blackbody temperatures.

Discrepancies of the order of 50% in the spectral region between 180 and 194 nm are difficult to explain. The results of Heroux and Swirbalus (1976) were obtained by means of a rocket-borne spectrometer and a photon counter and have an accuracy of ±20%. The Cs I photocathode which was used in their instrument shows a rapid decay in efficiency for wavelengths greater than 180 nm (see Figure 1 in Heroux and Swirbalus, 1976) which sets an upper limit at 194 nm to their spectra. On the other hand, Rottman (1974), who also used a photomultiplier with the same photocathode gives results only below 185 nm with an accuracy of ±15%. Therefore, it seems that such measurements lead to less precise values of the solar flux in the neighbourhood of 190 nm because of the lower detector efficiencies.

Our results have an accuracy of ±30%, taking into account all possible sources of error on the photographic intensity calibration, instrumental sensitivity and center-to-limb variation. Consequently, we consider that there is a strong need, for aeronomic purposes, for further and more precise measurements, especially between 180 and 200 nm, since our results should give an upper limit while those of Heroux and Swirbalus (1976), should give a lower limit for the solar irradiation flux between 180 and 194 nm.

TABLE I

Solar irradiation fluxes integrated over 1 nm between 151 and 209 nm at one astronomical unit.

Wavelength interval (nm)	Irradiance	
	$h\nu$ s^{-1} cm^{-2} nm^{-1}	mW m^{-2} nm^{-1}
151–152	5.29×10^{9}	6.94×10^{-2}
152–153	6.04	7.86
153–154	6.28	8.13
154–155	9.62	1.24×10^{-1}
155–156	8.44	1.08
156–157	8.42	1.07
157–158	8.44	1.06
158–159	8.47	1.06
159–160	8.69	1.08
160–161	9.62	1.19
161–162	1.11×10^{10}	1.37
162–163	1.23	1.50
163–164	1.38	1.67
164–165	1.59	1.92
165–166	2.32	2.78
166–167	1.69	2.01
167–168	1.91	2.26
168–169	2.21	2.60
169–170	2.98	3.49
170–171	3.53	4.11
171–172	3.70	4.28
172–173	4.30	4.95
173–174	4.39	5.03
174–175	5.49	6.25

Table I (*Continued*)

Wavelength interval (nm)	Irradiance	
	$h\nu\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{nm}^{-1}$	$\mathrm{mW\ m}^{-2}\ \mathrm{nm}^{-1}$
175–176	7.37	8.53
176–177	8.51	9.58
177–178	1.15×10^{11}	1.29×10^{0}
178–179	1.32	1.47
179–180	1.29	1.43
180–181	1.54	1.69
181–182	2.00	2.19
182–183	1.86	2.02
183–184	1.97	2.13
184–185	1.66	1.79
185–186	1.91	2.04
186–187	2.37	2.53
187–188	2.66	2.81
188–189	2.80	2.95
189–190	2.93	3.08
190–191	2.94	3.06
191–192	3.33	3.45
192–193	3.48	3.59
193–194	2.54	2.61
194–195	4.46	4.56
195–196	4.27	4.34
196–197	4.86	4.91
197–198	4.87	4.90
198–199	4.92	4.93
199–200	5.53	5.50
200–201	6.25	6.19
201–202	6.30	6.21
202–203	6.42	6.30
203–204	7.63	7.45
204–205	8.96	8.70
205–206	9.20	8.89
206–207	9.65	9.28
207–208	1.13×10^{12}	1.08×10^{1}
208–209	1.27	1.21

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