ULTRAVIOLET SOLAR IRRADIANCE MEASUREMENT FROM 200 TO 358 NM DURING SPACELAB 1 MISSION

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Abstract. The paper presents the results obtained from the UV-spectrometer of the 'Solar Spectrum Experiment' during the Spacelab 1 mission in December 1983. The irradiance data concern 492 passbands, which are located between 200 and 358 nm at almost equidistant wavelengths separated by about 0.3 nm. The passbands have a well-defined, bell-shaped profile with a full width at half maximum of about 1.3 nm. The data, which have an error budget between 4 and 5%, agree closely with the spectral distributions observed by Heath (1980) and Mentall *et al.* (1981) and confirm that the solar irradiance and the fluxes of Sun-like stars show about the same spectral distribution down to at least 240 nm.

1. Introduction

The need of accurate solar radiation data, e.g., in aeronomie and solar physics, has been emphasized by many authors and need not be pointed out once more (see, e.g., Simon, 1981). This paper presents new spectral irradiance data for the spectral region between 200 and 358 nm, which follow from measurements made on board of the space shuttle 'Columbia' during the Spacelab 1 mission in November–December 1983. The new instrumentation to measure the solar irradiance between 200 and 3000 nm from space was developed since 1977 with the aim to improve our knowledge not only about the absolute level and the spectral distribution of the irradiance, but also about its possible variations to be deduced from periodic flights with a good time coverage of the solar cycle. It should be recalled that at that time (≈ 1977) even in the visible spectral region the mostly used irradiance data showed differences in the order of 10%, in extreme cases even up to 30% (compare, e.g., the compilation by Pierce and Allen, 1977). In the UV – say between 200 and 300 nm – the discrepancies between the available data were even worse. A detailed analysis demonstrated their inadequacy for an unambiguous interpretation in terms of solar variability during the solar cycle 20 (see, e.g., Simon, 1978).

Since then the situation was improved significantly: the irradiance data provided by Neckel and Labs (1984) for the spectral region between 330 and 1250 nm must be supposed to have an absolute accuracy of 1% or better (compare, e.g., Neckel, 1984).

In the UV the limits of possible variations can now be estimated. Measurements performed from the 'Solar Mesosphere Explorer' satellite (SME) indicate that for wavelengths longer than 180 nm such variations can hardly be larger than a few percent,

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except, of course, for chromospheric emission lines (London *et al.*, 1984). Also the 4 rocket observations made by Mount and Rottman (1981, 1983a, b, 1985) between July 1980 and July 1983 agree above 200 nm within observational errors and rule out significant solar variations during that period (Mount and Rottman, 1985). Between 200 and 310 nm the standard deviations with respect to the averages of the four observations range between 1.2 and 4.2%.

Taking also into account the absolute irradiance data of Heath (1980) and of Mentall *et al.* (1981), it seems that also for wavelengths between 200 and 330 nm the uncertainty of the irradiance has been noticeably narrowed since 1977. Nevertheless, there are still significant differences between the data of Heath (1980) and Mentall *et al.* (1981) on one side and those of Mount and Rottman (1985) on the other side (compare, e.g., the compilation by Simon and Brasseur, 1983; and our Figure 9).

The measurement principle for the 'Solar Spectrum Experiment' is to compare the Sun with radiometric sources, using a blackbody as primary standard and tungsten and deuterium lamps as transfer standards. The comparison is made as differentially as possible; it follows the procedure used by Labs and Neckel (1962) in measuring the absolute disk-center intensities between 330 and 1250 nm from a ground-based station. The radiometric scale is transferred from the blackbody to the transfer sources using the solar spectrometer itself.

Unfortunately, our inflight calibration equipment failed to control the absolute responsivity-ratio between ground and orbit. Therefore, the irradiance data obtained for the spectral region above 360 nm are certainly not more reliable than those being already available in the literature. But assuming that the responsivity-ratio between orbit and pre-flight calibration was 1.00 (see Section 4), as was done for all previously published data obtained in space, for the ultraviolet domain (200–358 nm) reliable data were obtained, which have an error budget of only 5.2% at 200 nm; these UV-data are presented in this paper. For an overall-report of the 'Solar Spectrum Experiment' on Spacelab 1 we refer to Thuillier *et al.* (1984).

2. Instrumentation

The instrument includes three spectrometers, which are double monochromators using concave holographic gratings of 10 cm focal length as dispersion optics; they are used in the first order. These spectrometers cover simultaneously the ultraviolet, visible, and infrared domains. The scanning of the spectrum is made by setting the six gratings, which are mounted in the same mechanical rotating shaft, at discrete positions by means of a stepping motor. The bandpass-profiles of the spectrometers are bell-shaped. Transmitting diffusers ('grinds') are placed in front of the entrance slits in order to insure a full illumination of the gratings, to reduce errors resulting from small drift in the solar pointing and to allow the measurement of the inflight calibration source output. A schematic view of the instrumentation with all calibration devices discussed below is given in Figure 1. A more detailed description was given by Thuillier *et al.* (1981).

The specifications of the *UV-spectrometer* are given in Table I. Here we note that the

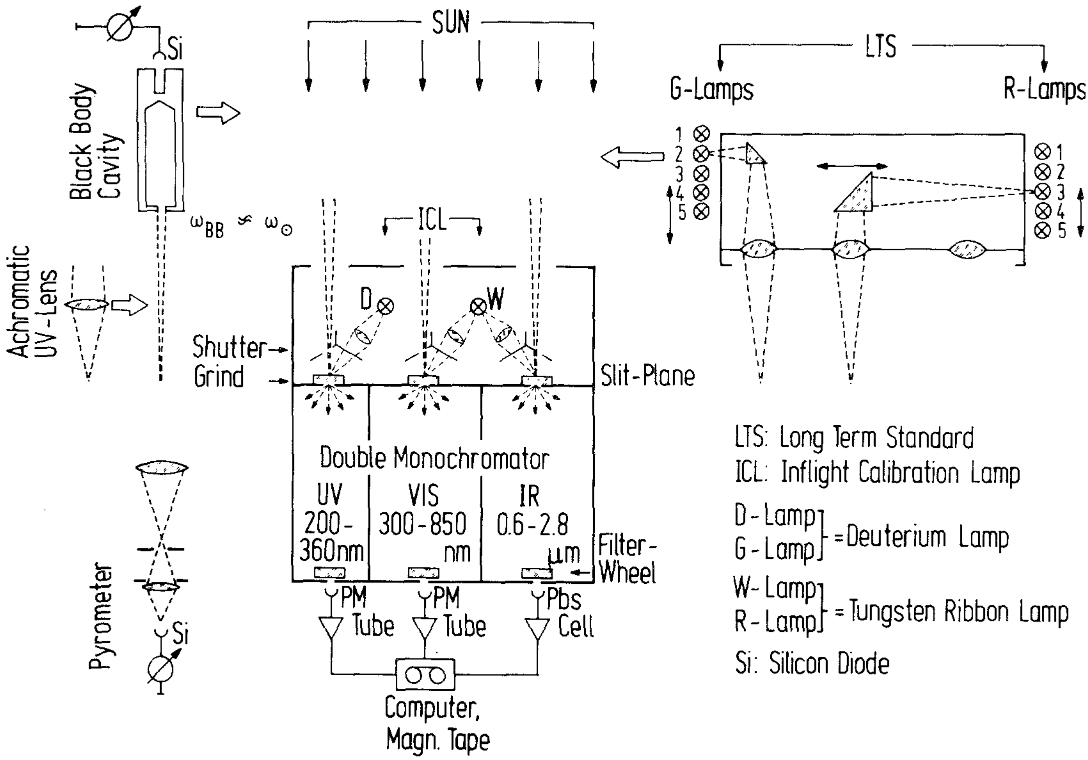

Fig. 1. Scheme of the spectrometer and its calibration device. The slits of the three double monochromators (UV, VIS, IR) are lit (a) in orbit either by the – imaged – inflight calibration lamps (ICL's: D- and W-lamps) or by the Sun, (b) at Kennedy Space Center (before and after the flight) either by the ICL's or by the – imaged – long-term standards (LTS: G- and R-lamps), (c) in the laboratory either by the ICL's, or by the LTS, or by the blackbody (either its irradiance with $\omega_{BB} \approx \omega_\odot$ or its imaged output diaphragm). The blackbody temperature is determined by a pyrometer and stabilized via a photodiode lit by the backside of the cavity.

TABLE I

Specifications of the UV-spectrometer (upper part) and of the blackbody (lower part)

Spectral range	200–360 nm	grind material	Suprasil I
Gratings:		field of view	7 °
manufacturer	Jobin Yvon	entrance slit	0.4 × 1.0 mm^2
diameter	30 mm	width of passband	
ruled area diam.	28 mm	FWHM at 200 nm	1.45 nm
ruling frequency	3600 g mm^{-1}	at 360 nm	1.17 nm
curvature radius	96.3 mm	'solar step' size	≃0.3 nm
focal length	99.42 mm	(10 grating steps)	
($\lambda \simeq 200$ nm)		detector type	EMR 641 F
coating	Al + MgF_2	window	MgF_2
Filter ($\lambda > 300$ nm)	Schott WG 280	photocathode	CsTe
Blackbody cavity	graphite	diphragm area	48.68 mm^2
Gas flushing	pure argon	distance from entrance slit	862.7 mm
Temperature	3000–3200 K	solid angle	6.54 × 10^{-5} ster

detector is a solar-blind photomultiplier tube with a CsTe side-on photocathode working in the pulse counting mode. Its dark count is only 2 cps. For wavelengths longer than 300 nm a higher order separation filter (Schott WG 280) is set in the optical path. The stray light when looking towards the Sun is of the order of 50 cps, with no wavelength dependence.

3. Calibration

The absolute calibration of the instrument has been performed at the Heidelberg Observatory by using a blackbody without window. The solid angle of its output diaphragm as seen from the spectrometer entrance slits is very close to that of the Sun. Further details are included in Table I. The temperature of the blackbody ($\approx$3000 K) was determined before and after each blackbody spectral run by a pyrometer, which was calibrated at the Physikalisch-Technische Bundesanstalt (PTB). During the runs the temperature was stabilized by means of the output of a silicon photodiode, which was lit by the backside of the cavity. (N.B.: one blackbody spectral run took about 15 min.)

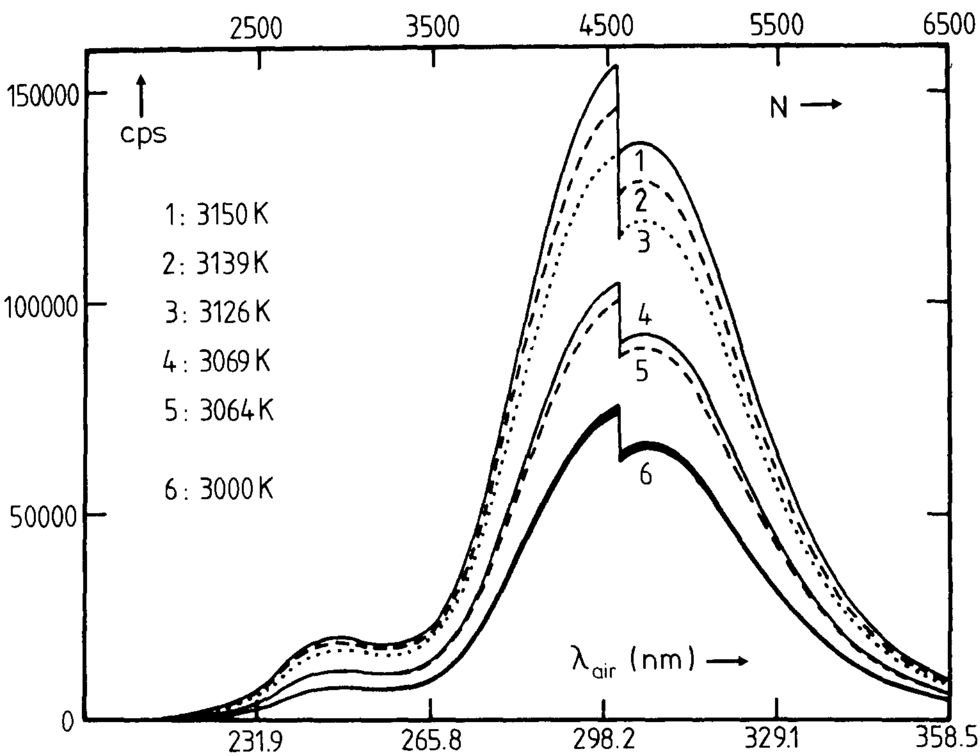

Fig. 2. Signals from imaged blackbody diaphragm (in counts per second) as a function of grating step number N and wavelength λ_{air}. Five selected spectra (1–5) obtained at different blackbody temperatures are displayed, as well as the final reference spectrum (6), which results from a reduction of all observed spectra to the common temperature of 3000 K. The step near 300 nm is due to the insertion of a higher-order separation filter.

Since the signal of the blackbody *irradiance* drops below 100 cps for wavelengths shorter than 300 nm, the solid angle of the blackbody radiation can be increased by using a quartz achromatic lens which images the blackbody output diaphragm on the ultraviolet entrance slit. The gain factor curve, which is nearly proportional to the transmission of the UV-lens, followed from special measurements made at 11 selected wavelengths. Figure 2 shows some examples of calibration curves obtained with the lens at different blackbody temperatures and the final blackbody ultraviolet spectrum, when all signals have been reduced to the same temperature, namely 3000 K.

Because the blackbody output drops below 10 cps for wavelengths shorter than 240 nm, instrument calibration has also been performed by using 3 deuterium lamps calibrated at the National Bureau of Standards (NBS). Their signal at 200 nm was about 200 cps. The comparison between blackbody and deuterium results is illustrated in Figure 3. For wavelengths shorter than 240 nm we adopted the responsivity following from the deuterium lamps, after adjustment to the blackbody results between 240 and 260 nm. The final, overall (pre-flight) responsivity of the UV-spectrometer is shown in Figure 4.

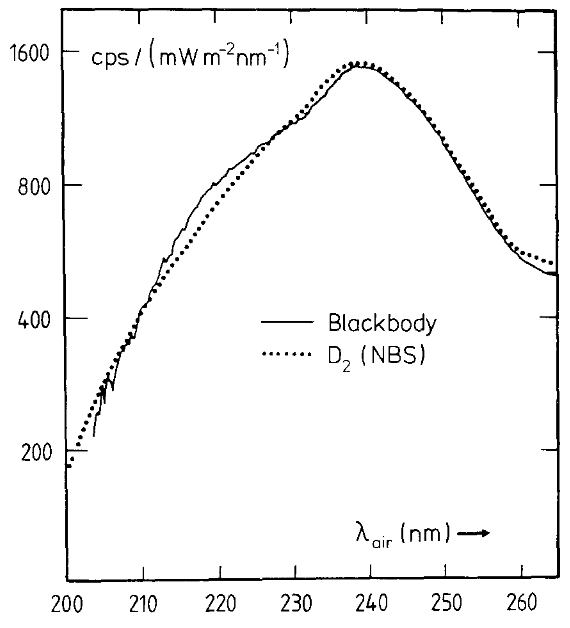

Fig. 3. Responsivity of the UV-spectrometer below 260 nm as obtained from the blackbody and from three deuterium standard lamps calibrated at the National Bureau of Standards (NBS).

To control the responsivity of the spectrometer during integration and subsequent tests at Kennedy Space Center and in orbit, two different sets of lamps were designed and used, namely the Long-Term Standard (LTS) and the Inflight Calibration Lamps (ICL's).

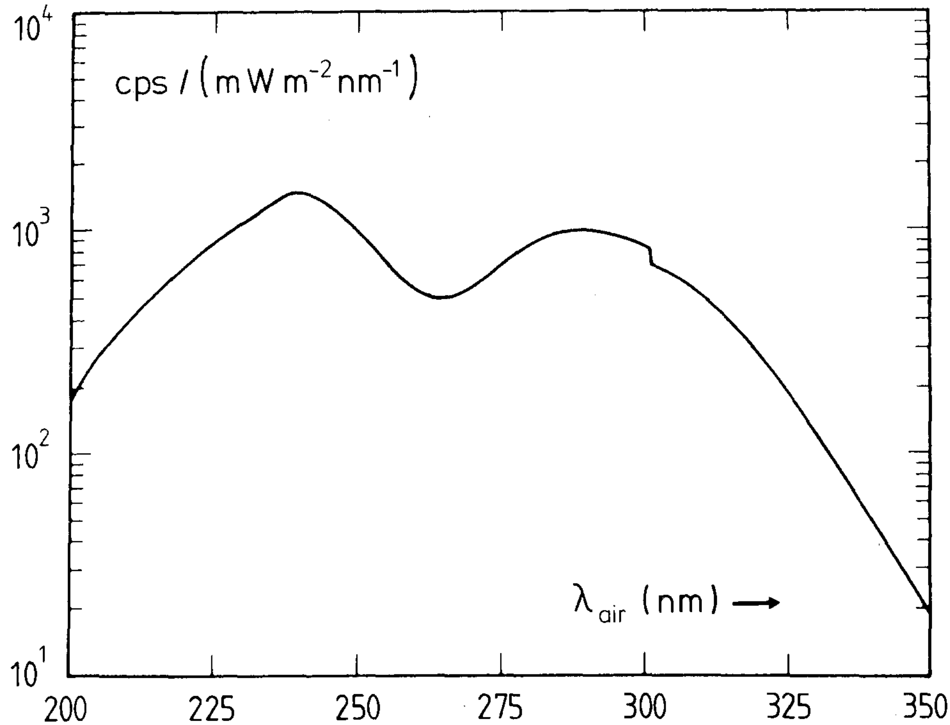

Fig. 4. The overall responsivity of the UV-spectrometer. The step near 300 nm results from the insertion of a higher-order separation filter.

The LTS-unit, which includes 5 pre-aged tungsten ribbon lamps (long-term stability about 0.5% per 100 hours burning time) and 5 deuterium lamps, can be fitted to the instrument during any ground operation, including calibration with the primary standard (blackbody) and comparison with the ICL's, when the instrument is already integrated on the pallet. The positions of the lamps, which are imaged on the entrance slit (compare Figure 1), are adjusted at each calibration run for maximum signal.

The second set of lamps is integrated in the instrument and includes 5 inflight calibration lamps (ICL's) developed by Hanau Heraeus GmbH. They can be operated at any time. Their main purpose is to check the instrument responsivity for short time coverage, mainly between the last pre-flight and first post-fligth LTS calibration. Two deuterium lamps are alternately used for the ultraviolet spectrometer. They are extensively described by Finkenzeller and Labs (1979). The lamp-spots are imaged on the entrance slit with the optical axis being inclined with respect to the normal of the diffuser (compare Figure 1). This is one of the reasons why a grind is required in front of the entrance slit. One hollow cathode lamp is also used during ground calibration and orbit observation to check the wavelength scale and the bandpass of the instrument by means of seven emission lines of helium and copper. All ICL's and their optics are mounted in a rigid structure; after final integration further adjustment of their positions relative to the entrance slit is not possible.

The relation between wavelength λ and (elementary) grating step number N (1 to 6500), which was defined in the laboratory with an accuracy of ± 0.05 nm by using emission lines from several spectral sources, is given by

$$\lambda(\text{nm}) = 140.741 + 0.0383197 \times N - 0.74054 \times 10^{-6} \times N^2. \quad (1)$$

It should be emphasized that for a given step number N the wavelength λ computed from (1) is the *air*-wavelength, if the measurements are made in the laboratory, but the *vacuum*-wavelength for measurements made in orbit. In this paper all quoted wavelengths are in the air-system.

The passband-profile of the UV spectrometer was measured by means of low pressure spectral lamps; it is given in Figure 5 and Table II as a function of step number. The full width at half maximum (FWHM) is constant with the step number and, consequently, decreasing from 1.45 to 1.17 nm with increasing wavelength.

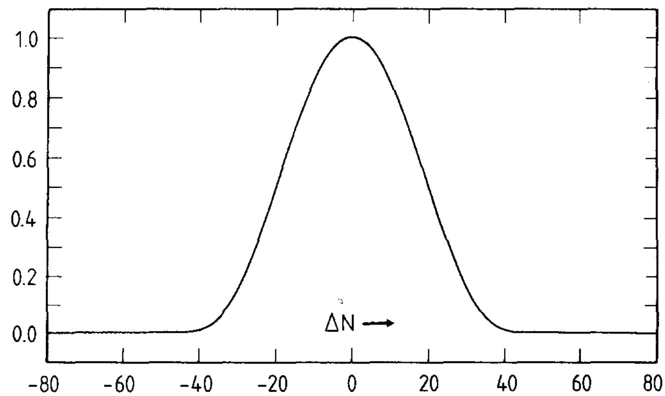

Fig. 5. The passband-profile of the UV-spectrometer as a function of the difference ΔN between the grating step number N and the step number at the passband-center. The profile is symmetric and does not depend on the central grating step number. (N.B.: These statements are not true if the profile is plotted against $\Delta\lambda$ instead ΔN. Compare Equation (1).)

The dead time (τ) of the pulse counting electronics was also determined in the laboratory by using neutral density filters; it defines the relation between the true and the measured number of counts per second

$$\text{cps}_{\text{true}} = \text{cps}_{\text{meas}}/(1 - \tau \times \text{cps}_{\text{meas}}), \quad (2)$$

with $\tau = (3.60 \pm 0.05) \times 10^{-7}$ s. This equation was used for linearity corrections due to statistical losses.

4. Observations

Solar spectral irradiance measurements were performed during Spacelab 1 mission from the space shuttle 'Columbia'. The 'Solar Spectrum Experiment' was integrated on

TABLE II

The normalized [$p(0) = 1$] passband-profile $p(\Delta N)$ of the UV-spectrometer. ΔN = distance from passband-center in grating steps.

ΔN	$p(\Delta N)$	ΔN	$p(\Delta N)$	ΔN	$p(\Delta N)$	ΔN	$p(\Delta N)$	ΔN	$p(\Delta N)$
0	1.0000	19	0.5367	38	0.0235	57	0.0036	76	0.0017
1	0.9980	20	0.4965	39	0.0176	58	0.0035	77	0.0016
2	0.9937	21	0.4573	40	0.0134	59	0.0034	78	0.0015
3	0.9867	22	0.4182	41	0.0105	60	0.0033	79	0.0015
4	0.9750	23	0.3792	42	0.0090	61	0.0032	80	0.0014
5	0.9622	24	0.3416	43	0.0080	62	0.0031	81	0.0014
6	0.9469	25	0.3058	44	0.0073	63	0.0030	82	0.0013
7	0.9286	26	0.2713	45	0.0069	64	0.0029	83	0.0012
8	0.9067	27	0.2399	46	0.0066	65	0.0028	84	0.0011
9	0.8835	28	0.2095	47	0.0063	66	0.0027	85	0.0010
10	0.8572	29	0.1801	48	0.0060	67	0.0026	86	0.0009
11	0.8291	30	0.1534	49	0.0057	68	0.0025	87	0.0008
12	0.7990	31	0.1287	50	0.0054	69	0.0024	88	0.0007
13	0.7665	32	0.1068	51	0.0051	70	0.0023	89	0.0005
14	0.7311	33	0.0869	52	0.0048	71	0.0022	90	0.0004
15	0.6893	34	0.0694	53	0.0045	72	0.0021	91	0.0003
16	0.6517	35	0.0543	54	0.0042	73	0.0020	92	0.0002
17	0.6142	36	0.0413	55	0.0040	74	0.0019	93	0.0001
18	0.5758	37	0.0316	56	0.0038	75	0.0018	94	0.0000

the European bridge of the Spacelab pallet. The launch was on 28 November, 1983 at 11 hr UT from Kennedy Space Center (KSC) for a 10 days mission. The orbit had an altitude of 250 km and an inclination of 57°. Solar spectral observations were made on 5 and 6 December within two periods of, respectively, 7 and 6 hr duration. The main observation sequence in orbit, called normal mode, includes measurements of, alternately, solar and ICL's radiation. The grating positioning was made every 10 (elementary) steps when looking towards the Sun and every 30 steps when measuring ICL's radiation. So, the total wavelength scanning was performed with 650 grating positions for the Sun and 216 grating positions for ICL's. In both cases, the integration time for pulse counting was 1 s.

Twenty-six solar spectra were finally obtained from real time and playback data. As the shuttle orbit was nearly above the terminator, between day and night, for a few so-called full sunlit orbits the line-of-sight between the shuttle and the Sun was occasionally passing through the Earth's atmosphere. To avoid possible atmospheric absorption, 7 spectra taken at a tangent height less than 100 km were rejected. The repeatability of undisturbed spectra was within $\pm 2\%$ (r.m.s. error). Figure 6 shows the spectral distribution of the solar signals obtained in orbit (mean of the 19 undisturbed spectra), after linearity corrections.

For reasons not yet clearly understood, the UV ICL's equipment (deuterium lamps, optics, and mounting) failed to control the response-ratio between ground and orbit. Nevertheless, the relative spectral *distribution* of the ICL's ultraviolet output before,

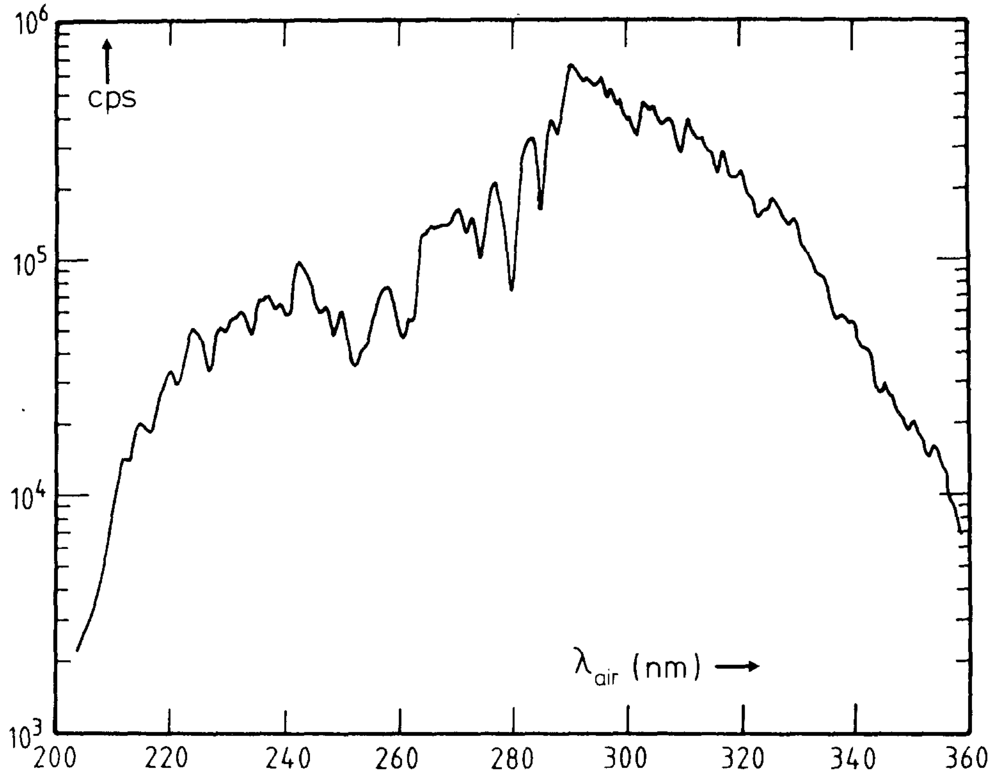

Fig. 6. The Sun's signals as a function of (air-) wavelength λ_{air} (mean of the 19 undisturbed spectra).

during and after the flight is in agreement within $\pm 5\%$. The hollow cathode lamp worked well and provided correct information on the passband-profile which did not change during flight. No significant change in the wavelength scale has been found between the observations in orbit (December 1983) and the blackbody calibration in Heidelberg (April 1984).

With respect to the ground operations at KSC, two LTS calibrations were performed before launch, in March and June 1983, and one after landing in January 1984. A fourth LTS calibration was performed in April 1984 in relation with the blackbody calibration in Heidelberg. In the following these calibrations will be respectively denoted as KSC 1, KSC 2, KSC 3, and HD.

Significant divergences between KSC 2 and KSC 3 calibrations were found for the ultraviolet spectrometer responsivity by means of the LTS calibrations, showing a strong wavelength dependence. The signal ratios illustrating the degradation are shown in Figure 7. They are based on the tungsten ribbon lamps down to 232 nm and below this wavelength on the deuterium lamps. The causes of this degradation cannot be explained. However, the last LTS calibration performed in Heidelberg revealed that the spectrometer responsivity had recovered about half the way to its original value (see Figure 7). The question when the degradation occurred and, consequently, which LTS

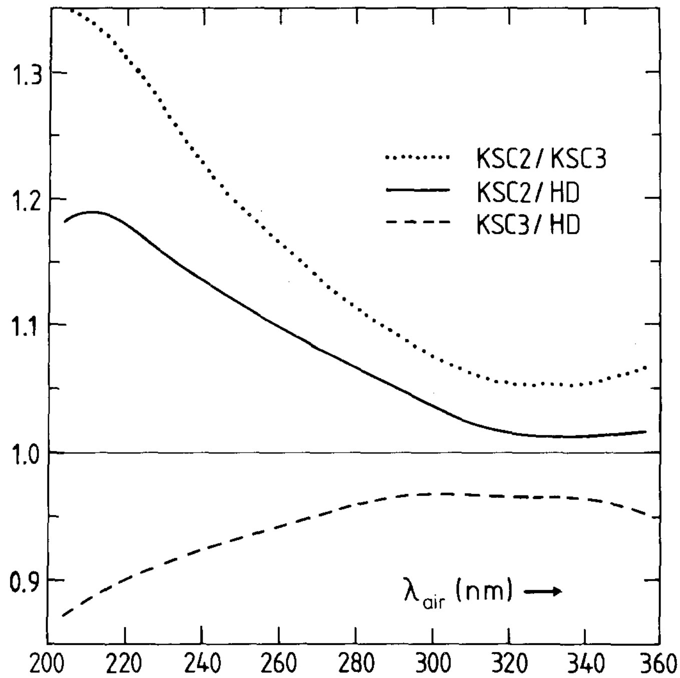

Fig. 7. Responsivity ratios obtained from the long-term standards (R-lamps for $\lambda > 232$ nm, G-lamps for $\lambda < 232$ nm). They demonstrate (a) the strong degradation between last pre-flight (KSC 2) and first post-flight (KSC 3) LTS calibration, and (b) a half-way recovery between KSC 3 and the Heidelberg (HD) calibration made three months later. There are strong indications – and the data reduction is based on the supposition – that the degradation occurred *after* the observations in orbit.

calibration – KSC 2 or KSC 3 – is the more reliable one, was solved by a careful analysis of the ICL's and solar data. The following facts indicate that the degradation occurred *after* the solar observations: (1) the ratios of the ICL's signals between calibration KSC 2 and KSC 3 are similar to the ratios of the LTS signals obtained at the same time, and show the same wavelength tendency; (2) a responsivity change in orbit of 30% around 220 nm is not indicated by the deuterium spectra recorded all along the mission; (3) the solar ultraviolet signal varies only within 2% over 13 hr of observation; (4) the instrument partially recovered its responsivity from January to April, indicating that the degradation is *non*-permanent, which is usually not the case for the well-known optical degradation induced by solar X-ray and far-UV radiation. Consequently, the reduction of the solar observations was done assuming no change in the spectrometer responsivity between KSC 2 and orbit. Nevertheless, systematic differences of the order of 5% between ground and orbit cannot be excluded, as it was of course the case for all previous solar radiation measurements made in space.

TABLE III

Solar irradiance at 1 AU for 492 passbands with profiles defined in Table II and Figure 5. λ = (air-) wavelength of passband-center in nm, $\bar{s}$ = profile-averaged irradiance (see Equation (3)) in W m^{-2} nm^{-1} (5.432–1 = 5.432 × 10^{-1})

λ	$\bar{s}$	λ	$\bar{s}$	λ	$\bar{s}$	λ	$\bar{s}$	λ	$\bar{s}$
199.73	6.483-3	217.53	3.704-2	234.95	4.654-2	252.00	4.044-2	268.68	2.591-1
200.09	6.562-3	217.88	4.095-2	235.29	4.958-2	252.34	4.100-2	269.01	2.566-1
200.45	6.698-3	218.23	4.319-2	235.64	4.925-2	252.68	4.344-2	269.34	2.611-1
200.81	6.972-3	218.58	4.431-2	235.98	4.831-2	253.01	4.688-2	269.67	2.782-1
201.17	7.171-3	218.93	4.501-2	236.33	4.762-2	253.35	5.045-2	270.00	2.888-1
201.53	7.435-3	219.29	4.646-2	236.67	4.844-2	253.69	5.345-2	270.33	2.946-1
201.89	7.426-3	219.64	4.859-2	237.02	4.951-2	254.02	5.544-2	270.66	2.875-1
202.25	7.498-3	219.99	4.970-2	237.36	4.753-2	254.36	5.867-2	270.99	2.717-1
202.61	7.747-3	220.34	4.680-2	237.70	4.372-2	254.70	6.414-2	271.32	2.443-1
202.96	8.068-3	220.69	4.244-2	238.05	4.154-2	255.03	7.193-2	271.65	2.187-1
203.32	8.497-3	221.04	3.949-2	238.39	4.203-2	255.37	7.880-2	271.98	2.086-1
203.68	8.845-3	221.39	3.991-2	238.73	4.353-2	255.70	8.455-2	272.31	2.206-1
204.04	9.355-3	221.74	4.272-2	239.08	4.379-2	256.04	9.121-2	272.63	2.365-1
204.40	9.685-3	222.09	4.637-2	239.42	4.298-2	256.38	1.026-1	272.96	2.363-1
204.75	9.932-3	222.44	5.031-2	239.76	4.151-2	256.71	1.124-1	273.29	2.146-1
205.11	1.001-2	222.79	5.536-2	240.10	4.014-2	257.05	1.189-1	273.62	1.836-1
205.47	9.922-3	223.14	5.988-2	240.45	3.930-2	257.38	1.245-1	273.95	1.580-1
205.83	1.011-2	223.49	6.164-2	240.79	4.107-2	257.72	1.273-1	274.27	1.473-1
206.18	1.049-2	223.84	6.064-2	241.13	4.654-2	258.05	1.263-1	274.60	1.524-1
206.54	1.078-2	224.19	5.913-2	241.47	5.466-2	258.39	1.255-1	274.93	1.686-1
206.90	1.146-2	224.54	5.691-2	241.82	6.252-2	258.72	1.232-1	275.25	1.944-1
207.25	1.196-2	224.89	5.464-2	242.16	6.791-2	259.05	1.151-1	275.58	2.250-1
207.61	1.248-2	225.24	5.178-2	242.50	6.994-2	259.39	1.035-1	275.91	2.498-1
207.96	1.344-2	225.59	4.783-2	242.84	6.851-2	259.72	9.472-2	276.23	2.672-1
208.32	1.459-2	225.94	4.376-2	243.18	6.616-2	260.06	9.099-2	276.56	2.766-1
208.68	1.622-2	226.28	3.873-2	243.52	6.489-2	260.39	8.742-2	276.89	2.782-1
209.03	1.845-2	226.63	3.571-2	243.86	6.357-2	260.72	8.566-2	277.21	2.640-1
209.39	2.067-2	226.98	3.556-2	244.20	6.131-2	261.06	8.797-2	277.54	2.377-1
209.74	2.331-2	227.33	3.931-2	244.54	5.724-2	261.39	9.624-2	277.87	2.110-1
210.10	2.572-2	227.68	4.472-2	244.89	5.304-2	261.72	1.047-1	278.19	1.855-1
210.45	2.747-2	228.03	4.904-2	245.23	4.977-2	262.06	1.080-1	278.52	1.576-1
210.81	2.952-2	228.37	4.990-2	245.57	4.835-2	262.39	1.066-1	278.84	1.285-1
211.16	3.196-2	228.72	4.930-2	245.91	4.759-2	262.72	1.135-1	279.17	1.027-1
211.52	3.316-2	229.07	4.744-2	246.25	4.866-2	263.05	1.416-1	279.49	8.701-2
211.87	3.245-2	229.41	4.570-2	246.59	5.104-2	263.39	1.888-1	279.82	8.443-2
212.23	3.110-2	229.76	4.657-2	246.93	5.313-2	263.72	2.340-1	280.14	9.784-2
212.58	3.019-2	230.11	4.964-2	247.27	5.395-2	264.05	2.570-1	280.47	1.262-1
212.94	3.009-2	230.46	5.084-2	247.60	5.162-2	264.38	2.582-1	280.79	1.639-1
213.29	3.200-2	230.80	5.009-2	247.94	4.809-2	264.71	2.569-1	281.12	2.072-1
213.64	3.507-2	231.15	4.944-2	248.28	4.435-2	265.05	2.639-1	281.44	2.508-1
214.00	3.840-2	231.49	4.959-2	248.62	4.383-2	265.38	2.727-1	281.76	2.852-1
214.35	3.975-2	231.84	5.080-2	248.96	4.801-2	265.71	2.749-1	282.09	3.115-1
214.71	3.933-2	232.19	5.114-2	249.30	5.425-2	266.04	2.712-1	282.41	3.321-1
215.06	3.762-2	232.53	4.957-2	249.64	5.843-2	266.37	2.647-1	282.74	3.449-1
215.41	3.604-2	232.88	4.681-2	249.98	5.955-2	266.70	2.642-1	283.06	3.504-1
215.76	3.466-2	233.22	4.420-2	250.31	5.850-2	267.03	2.677-1	283.38	3.507-1
216.12	3.360-2	233.57	4.089-2	250.65	5.464-2	267.36	2.692-1	283.71	3.401-1
216.47	3.243-2	233.91	3.793-2	250.99	4.994-2	267.69	2.692-1	284.03	3.130-1
216.82	3.191-2	234.26	3.736-2	251.33	4.545-2	268.02	2.673-1	284.35	2.629-1
217.17	3.336-2	234.61	4.078-2	251.67	4.228-2	268.35	2.623-1	284.67	2.036-1

Table III (continued)

λ	$\bar{s}$	λ	$\bar{s}$	λ	$\bar{s}$	λ	$\bar{s}$	λ	$\bar{s}$
285.00	1.660-1	300.94	5.145-1	316.51	7.264-1	331.71	1.037 0	346.54	1.006 0
285.32	1.805-1	301.25	5.109-1	316.82	8.186-1	332.01	1.024 0	346.84	1.010 0
285.64	2.375-1	301.57	4.835-1	317.13	8.596-1	332.31	1.021 0	347.13	9.727-1
285.96	3.028-1	301.88	4.812-1	317.43	8.258-1	332.61	1.012 0	347.42	9.469-1
286.29	3.527-1	302.20	5.223-1	317.74	7.545-1	332.91	1.007 0	347.71	9.412-1
286.61	3.842-1	302.51	5.957-1	318.05	7.149-1	333.21	9.785-1	348.01	9.534-1
286.93	3.957-1	302.83	6.726-1	318.35	7.179-1	333.51	9.719-1	348.30	9.755-1
287.25	3.793-1	303.14	7.005-1	318.66	7.285-1	333.81	9.891-1	348.59	9.590-1
287.57	3.446-1	303.46	6.855-1	318.97	7.428-1	334.11	1.016 0	348.88	9.308-1
287.89	3.320-1	303.77	6.710-1	319.27	7.622-1	334.41	1.026 0	349.17	9.144-1
288.21	3.517-1	304.08	6.629-1	319.58	7.955-1	334.71	1.040 0	349.47	9.467-1
288.54	3.905-1	304.40	6.742-1	319.89	8.462-1	335.01	1.056 0	349.76	1.031 0
288.86	4.414-1	304.71	7.003-1	320.19	8.849-1	335.31	1.028 0	350.05	1.103 0
289.18	4.978-1	305.02	6.960-1	320.50	8.623-1	335.60	9.511-1	350.34	1.141 0
289.50	5.567-1	305.34	6.584-1	320.80	7.979-1	335.90	9.087-1	350.63	1.121 0
289.82	6.152-1	305.65	6.314-1	321.11	7.529-1	336.20	8.737-1	350.92	1.069 0
290.14	6.489-1	305.96	6.170-1	321.42	7.506-1	336.50	8.418-1	351.21	1.048 0
290.46	6.636-1	306.27	6.201-1	321.72	7.706-1	336.80	8.549-1	351.50	1.052 0
290.78	6.588-1	306.59	6.505-1	322.03	7.748-1	337.09	8.930-1	351.79	1.029 0
291.10	6.457-1	306.90	6.795-1	322.33	7.496-1	337.39	9.144-1	352.08	9.885-1
291.42	6.312-1	307.21	6.937-1	322.64	7.112-1	337.69	9.375-1	352.37	9.577-1
291.74	6.110-1	307.52	7.041-1	322.94	6.915-1	337.99	9.697-1	352.66	9.751-1
292.06	5.812-1	307.84	7.073-1	323.24	7.005-1	338.28	9.884-1	352.95	1.027 0
292.38	5.649-1	308.15	7.085-1	323.55	7.418-1	338.58	9.968-1	353.24	1.106 0
292.70	5.799-1	308.46	6.862-1	323.85	7.883-1	338.88	9.898-1	353.53	1.152 0
293.01	5.904-1	308.77	6.405-1	324.16	8.188-1	339.17	9.991-1	353.82	1.170 0
293.33	5.824-1	309.08	5.921-1	324.46	8.344-1	339.47	1.049 0	354.11	1.188 0
293.65	5.729-1	309.39	5.498-1	324.77	8.509-1	339.77	1.088 0	354.40	1.207 0
293.97	5.633-1	309.70	5.399-1	325.07	8.991-1	340.06	1.096 0	354.69	1.202 0
294.29	5.533-1	310.02	5.987-1	325.37	9.660-1	340.36	1.077 0	354.98	1.184 0
294.61	5.603-1	310.33	6.934-1	325.68	1.029 0	340.66	1.027 0	355.26	1.150 0
294.92	5.767-1	310.64	7.834-1	325.98	1.056 0	340.95	9.771-1	355.55	1.127 0
295.24	5.943-1	310.95	8.328-1	326.28	1.063 0	341.25	9.747-1	355.84	1.117 0
295.56	6.183-1	311.26	8.130-1	326.59	1.050 0	341.54	1.002 0	356.13	1.075 0
295.88	6.130-1	311.57	7.605-1	326.89	1.044 0	341.84	1.022 0	356.42	9.911-1
296.20	5.707-1	311.88	7.257-1	327.19	1.038 0	342.13	1.037 0	356.70	9.211-1
296.51	5.213-1	312.19	7.171-1	327.49	1.021 0	342.43	1.069 0	356.99	8.970-1
296.83	5.078-1	312.50	7.236-1	327.80	1.001 0	342.72	1.073 0	357.28	9.065-1
297.15	5.423-1	312.81	7.349-1	328.10	9.803-1	343.02	1.069 0	357.57	8.936-1
297.46	5.776-1	313.12	7.551-1	328.40	9.782-1	343.31	1.031 0	357.85	8.383-1
297.78	5.607-1	313.43	7.800-1	328.70	1.021 0	343.61	9.347-1	358.14	7.711-1
298.10	5.174-1	313.74	7.710-1	329.00	1.080 0	343.90	8.417-1	358.43	7.426-1
298.41	5.025-1	314.04	7.358-1	329.30	1.142 0	344.20	8.154-1		
298.73	5.177-1	314.35	7.206-1	329.61	1.180 0	344.49	8.484-1		
299.05	5.414-1	314.66	7.274-1	329.91	1.148 0	344.78	9.305-1		
299.36	5.384-1	314.97	7.283-1	330.21	1.099 0	345.08	9.879-1		
299.68	4.976-1	315.28	7.002-1	330.51	1.056 0	345.37	1.009 0		
299.99	4.614-1	315.59	6.499-1	330.81	1.036 0	345.66	9.741-1		
300.31	4.582-1	315.89	6.260-1	331.11	1.031 0	345.96	9.518-1		
300.62	4.825-1	316.20	6.510-1	331.41	1.043 0	346.25	9.670-1		

5. Results and Discussion

The air-wavelengths λ_i of the passband-centers and the resulting irradiance data

$$\bar{s}_i = \int p_i(\lambda) s(\lambda) \,\mathrm{d}\lambda \Big/ \int p_i(\lambda) \,\mathrm{d}\lambda \tag{3}$$

are compiled in Table III for all 492 observed passbands. $p_i(\lambda)$ is the apparatus-profile for passband-number $i (1 \leqq i \leqq 492)$, which follows from the profile-data given in Table II as a function of step-number and the step-number/wavelength relation given in Equation (1). A graphical presentation of these irradiance data is given in Figure 8, while the error budget is summarized in Table IV. It turns out that the mean errors of our data are arround $\pm 5\%$ whereby a possible systematic error due to a difference in the absolute responsivity between ground and orbit is neglected for reasons explained above. However, systematic errors in the overall spectral *distribution*, which exceed $\pm 5\%$, can be excluded.

Figure 9 shows the comparison of 10 nm spectral averages of the 'spacelab irradiance' with the results obtained by Heath (1980), Mentall *et al.* (1981), and Neckel and Labs (1984), and with the mean of the data provided by Mount and Rottman (1983a, b, 1985).

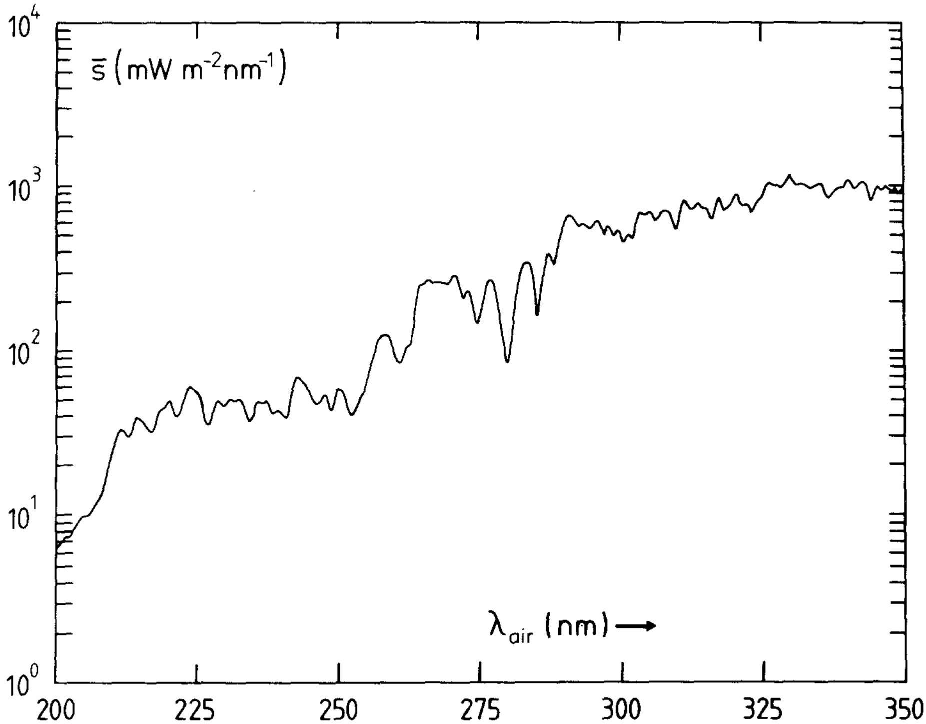

Fig. 8. The solar irradiance as observed with the UV-spectrometer: mean of 19 undisturbed spectra, after reduction to a Sun's distance of 1 AU. The absolute scale was obtained supposing that the responsivity in orbit was identical with that determined at the KSC 2 (pre-flight) calibration.

TABLE IV

Error budget

Wavelength	200 nm	240 nm	300 nm
Blackbody irradiance	–	4.2%	3.3%
Deuterium lamp irradiance	4.7%	–	–
Blackbody to LTS	–	2.0%	1.0%
Deuterium lamp to LTS	1.0%	–	–
LTS repeatability	0.3%	0.3%	0.3%
KSC calibration	0.3%	0.3%	0.3%
Repeatability of solar signal in orbit	2.0%	2.0%	2.0%
Total r.m.s. error	5.2%	5.1%	4.0%

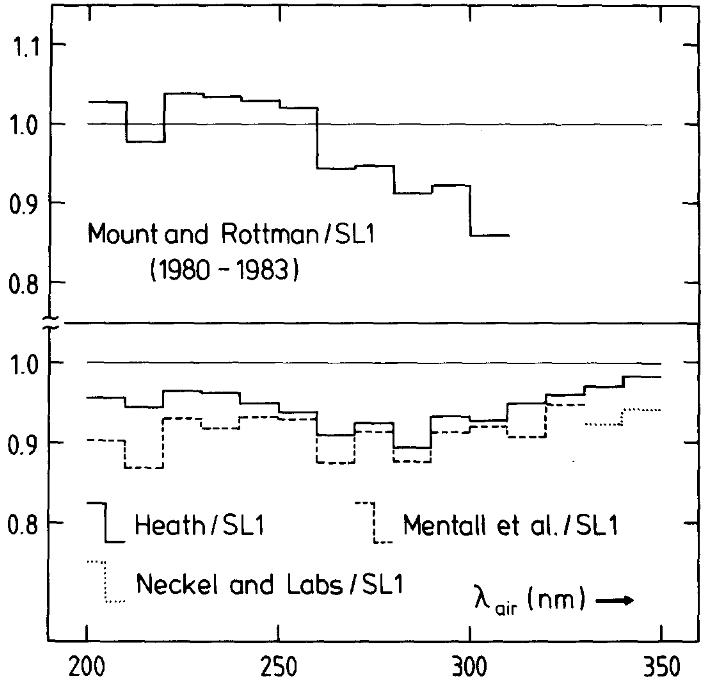

Fig. 9. Comparison of 10 nm spectral averages of solar irradiance published by Mount and Rottman (mean of 4 data sets published in 1981 (corrected 1983a), 1983a, b, 1985), Heath (1980), Mentall *et al.* (1981), Neckel and Labs (1984), with the Spacelab 1 results (SL 1). The plotted ratios follow from the numerical data given in Table V.

From these plots it appears to be very evident that the overall spectral *distribution* of the spacelab irradiance harmonizes well with the distributions of the data by Heath (1980) and Mentall *et al.* (1981), but does not match the distribution of the Mount and Rottman data. In particular, the step around 260 nm seems to indicate that the Mount and Rottman data are still affected by calibration errors which are of the same order of magnitude as the corrections applied by Mount and Rottman (1983a) to their previously published data (Mount and Rottman, 1981).

Evidence that the irradiance distributions shown in the lower part of Figure 9 are probably the more correct ones, comes from a comparison with the spectral flux distribution of the 'solar analog' 16 Cyg B, which was observed – together with the star 16 Cyg A – by Hardorp (1980; $\lambda > 330$ nm) and Hardorp *et al.* (1982; $\lambda < 330$ nm) down to 240 nm, using the IUE-satellite for wavelengths shorter than 330 nm. Figure 10, which is adopted from Hardorp *et al.* (1982), shows in the upper part the magnitude differences between the two stars 16 Cyg A and 16 Cyg B, and in the lower part between 16 Cyg B and the Sun. The solar data for $\lambda > 330$ nm come from Neckel and Labs (1981), for $\lambda < 330$ nm from Mount and Rottman (1981; circles). Although the discrepancy in the energy distributions below 330 nm is diminished if the corrected data of Mount and Rottman (1983a) are used, the corrections are much too small to achieve reasonable agreement. On the other hand, satisfying agreement of the spectral *distribution* is found if for the Sun the average irradiance values given in Table V are adopted (crosses in Figure 10). This leads to the conclusions that (a) the energy distributions of Heath (1980), of Mentall *et al.* (1981) and those obtained from the spacelab mission are nearly correct and (b) the close agreement in the spectra of Sun and 16 Cyg B continues down to at least 240 nm. Furthermore, from the good agreement between the two stars

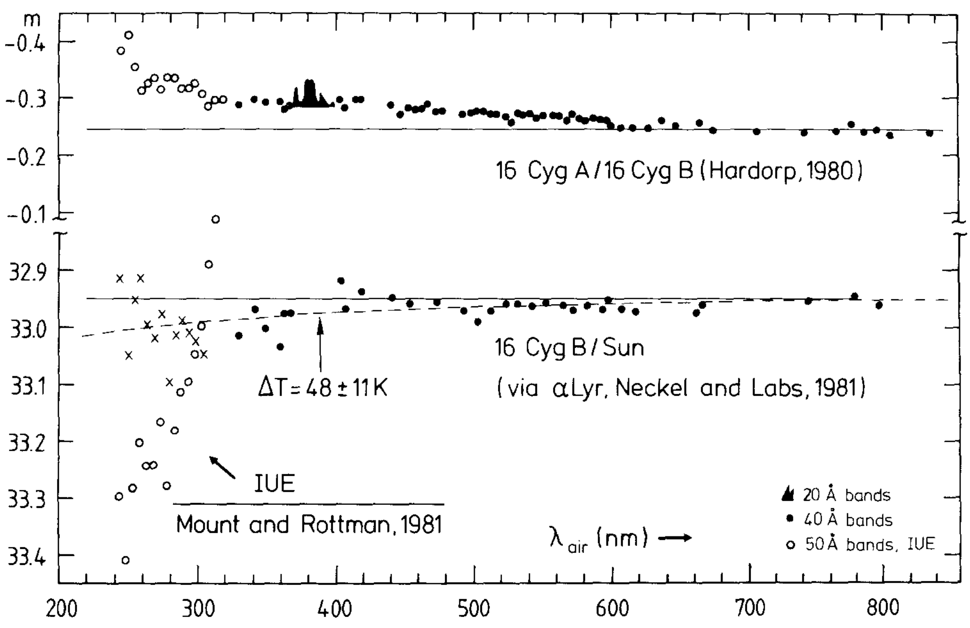

Fig. 10. Reproduction of a figure given by Hardorp *et al.* (1982) showing the magnitude differences between the two Sun-like stars 16 Cyg A and 16 Cyg B (upper part) and between 16 Cyg B and the Sun (lower part). The points follow from published data as indicated, the circles from IUE-observations (stars) and the (uncorrected) solar data of Mount and Rottman (1981). The crosses are added by us. They follow from the magnitude differences (16 Cyg B–Sun) plotted by Hardorp by adding the magnitude differences (mean of Table V minus Mount and Rottman data) and a constant ($-0^{m}.245$).

and between Sun and stars one must again conclude that above 240 nm significant variations in the spectra of Sun-like stars – the Sun included – are rather unlikely.

Figure 11 presents the data selected on the basis of their spectral distribution as explained above. They are referred to the irradiance averages defined in Table V. All measurements agree within their quoted uncertainties, the mean differences being only

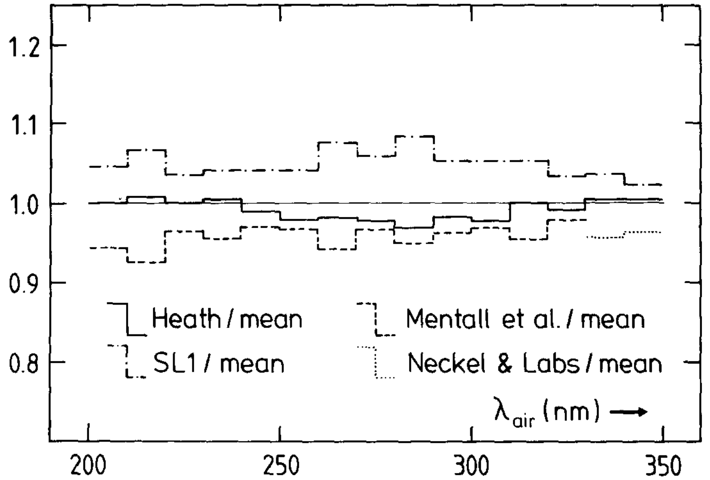

Fig. 11. The irradiance of (1) Heath (1980), (2) Mentall *et al.* (1981), (3) Neckel and Labs (1984), and (4) the Spacelab 1 experiment (SL 1) referred to their common mean values, which are included in Table V.

TABLE V

Solar irradiance at 1 AU averaged over 10 nm wide wavelength intervals, in 10^{12} photons cm^{-2} s^{-1} nm^{-1} (10^{12} photons s^{-1} = 0.1986/λ(nm) mW)

Wavelengths in nm	Heath (1980)	Mentall *et al.* (1981)	Neckel and Labs (1984)	SL 1 (this paper)	Mean of col. 2–5	Mount and Rottman (1981–1985)
200–210	1.08	1.02		1.13	1.08	1.16
210–220	3.68	3.38		3.90	3.65	3.81
220–230	5.24	5.05		5.43	5.24	5.64
230–240	5.24	4.99		5.44	5.22	5.63
240–250	6.29	6.17		6.63	6.36	6.82
250–260	9.57	9.48		10.2	9.75	10.4
260–270	25.4	24.4		27.9	25.9	26.3
270–280	26.7	26.4		28.9	27.3	27.4
280–290	40.5	39.7		45.3	41.8	41.3
290–300	79.4	77.7		85.2	80.8	78.6
300–310	87.7	86.9		94.5	89.7	81.2
310–320	112	107		118	112	
320–330	143	141		149	144	
330–340	163		155	168	162	
340–350	167		160	170	166	

of the order of $\pm 5\%$. The new data obtained during the Spacelab 1 mission give the upper limit for solar irradiance between 200 and 350 nm, while those of Mentall *et al.* (1981) combined with those of Neckel and Labs (1984) give the lower limit. With respect to the errors affecting all data sets we like to emphasize that it is certainly not advisable to interpret any differences in terms of solar variability.

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