issn 0065-3713

INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

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AERONOMICA ACTA

A - N° 338 - 1989

Solar spectral irradiances

with their diversity between 120 and 900 NM

by

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FOREWORD

"Solar spectral irradiances with their diversity between 120 and 900 nm" is the base of a review article to be published in Space Science Review.

AVANT-PROPOS

"Solar spectral irradiances with their diversity between 120 and 900 nm" est la base d'une analyse de l'irradiance spectrale solaire dont le texte sera publié dans Space Science Review.

VOORWOORD

"Solar spectral irradiances with their diversity between 120 and 900 nm" vormt de basis voor een recensie-artikel dat zal verschijnen in Space Science Review.

VORWORT

"Solar spectral irradiances with their diversity between 120 and 900 nm" ist die Basis für ein Übersichtstext der in Space Science Review erscheinen wird.

SOLAR SPECTRAL IRRADIANCES WITH THEIR DIVERSITY BETWEEN 120 AND 900 NM

by

Marcel NICOLET

ABSTRACT

Observations of the solar spectral irradiances from satellites, rockets and balloons, in addition to ground level and aircraft measurements, are of fundamental importance for a correct interpretation of aeronomic phenomena in the terrestrial and planetary atmospheres. An analysis of the limited amount of published data on the full-disk solar fluxes indicates clearly that more simultaneous and continuous measurements are needed to reduce the systematic differences between the various observed spectral irradiances. It is also important to reduce by precise calibrations the multiple random errors in order to permit meaningful studies of the variability of the solar fluxes. Permanent support by Space Agencies for multiple and long-term observations is required for the acquisition of a reliable data base of accurate spectral solar irradiances.

RESUME

L'observation de l'irradiance spectrale solaire à l'aide de satellites, de fusées et de ballons, sans exclure les mesures effectuées au sol et par avion, est d'une importance fondamentale en vue d'une interprétation correcte des phénomènes aéronomiques au sein des atmosphères terrestre et planétaires. Une analyse d'un nombre limité de données publiées sur le flux spectral du disque solaire montre clairement que plus de mesures continues et simultanées sont requises afin de réduire les différences systématiques apparaissant entre les diverses irradiances observées. Il est également important de réduire par des étalonnages précis les multiples erreurs accidentelles en vue de permettre une étude sérieuse de la variabilité des flux solaires. Les diverses Agences Spatiales doivent apporter leur support permanent aux projets d'observation à long terme et les multiplier afin d'obtenir une base sérieuse d'irradiances spectrales solaires précises.

SAMENVATTING

Waarnemingen van de spectrale zonne-uitstraling met behulp van satellieten, raketten en ballons, samen met metingen uitgevoerd vanop de grond en met vliegtuigen, zijn fundamenteel van belang voor een juiste verklaring van aëronomische verschijnselen in de aardse en planetaire atmosferen. Een analyse van het beperkt aantal gepubliceerde gegevens over de spectrale flux van de zonneschijf toont duidelijk dat meer gelijktijdige en ononderbroken metingen nodig zijn om de systematische verschillen tussen de diverse waargenomen spectrale uitstralingen te verminderen. Het is eveneens belangrijk door nauwkeurige ijkingen de veelvuldige toevallige fouten te beperken teneinde zinvolle studies van de veranderlijkheid van de zonnefluxen mogelijk te maken. De verschillende ruimteagentschappen moeten hun permanente steun verlenen aan de waarnemingsprojecten op lange termijn om aldus een betrouwbaar gegevensbestand van nauwkeurige spectrale zonne-uitstralingen te bekomen.

ZUSAMMENFASSUNG

Beobachtungen der spektralen Sonnenstrahlung mit Hilfe von Satelliten, Raketen und Ballons, zusammmen mit Messungen am Boden und am Bord von Flugzeugen ausgeführt, sind für eine korrekte Interpretation von aeronomischen Phänomenen in den irdischen und planetarischen Atmosphären sehr wichtig. Die Analyse der begrenzten Anzahl von publizierten Daten über den Spektralfluss der Sonnenscheibe zeigt deutlich dass mehr gleichzeitige und ununterbrochene Messungen nötig sind um die systematischen Unterschiede zwischen den verschiedenen beobachteten spektralen Ausstrahlungen zu reduzieren. Es ist auch wichtig die zahlreichen zufälligen Fehler durch genaue Eichungen zu verkleinern um vernünftige Studien der Variabilität der Sonnenflüsse zu ermöglichen. Raumagenturen sollen ihre beständige Hilfe für zahlreiche langfristige Beobachtungsprojekten leisten, um also die Bildung einer zuverlässigen Datenbank von präzisen spektralen Sonnenausstrahlungen zu ermöglichen.

1. INTRODUCTION

The total solar irradiance (solar constant) seems to have been measured with good accuracy from satellites (Wilson and Hudson, 1988; Meckerikunnel et al, 1988; ...). Apparently, the variation of the total irradiance during a solar cycle correspond to a change in the effective temperature of the Sun of between 1K and 2K, notwithstanding systematic differences, on the pyrheliometric scale of 0.2% to 0.4%, in the irradiance measurements that correspond to 3 and 5K, respectively.

However, accuracy is far from achievement in the measurements of the spectral irradiances, particularly in the ultraviolet region observed by balloons, rockets and satellites for many years (see for references, for example, Simon 1981 and 1989). An excellent example of the difficulties in obtaining a correct value is the Lyman-alpha line at 121.6 nm. This predominant line in the solar spectrum of atomic hydrogen is the most abundant element in the chromosphere, and has been observed for over 40 years. Ever since the attempt by Bossy and Nicolet (1981) to explain mystifying differences in the values of the solar spectral irradiances in terms of simple inhomogeneities in the observations, multiple suggestions have been made to account for the behaviour of the observed solar spectrum in the EUV. Its variability could not be correlated, in certain instances with such excellent proxies as the solar radiofluxes (see Nicolet and Bossy, 1985) in the cm region (10.7 cm, for example). A recent judicious example is given by Fukui (1988), who explains how an anomalous increase in Lyman-alpha observations could be the result of a secondary production mechanism in the solar atmosphere. However, this kind of astrophysical arguments that always centers on explanation of differences in unusual features detected somewhere on the solar disk cannot be utilized normal practise for aeronomic studies. The current spectroscopic detection of peculiar stars by satellite observations cannot be considered an example of accurate calibration to be adopted for our variable star, the Sun. It must be anticipated that, even though there is some suspicion of lack of accuracy in the results of the spectral irradiance observations, the precision revealed by comparison of

the various measurements should show to what degree it is possible to distinguish between real solar ultraviolet variability and the effects of instrumental variations.

In the present paper we will analyze some of the observations that we consider sufficiently representative of the recent solar spectral irradiance measurements. There is a need for critical analysis of such a basic aeronomic parameter at a time when an international ozone scientific assessment is ready to begin and an international geosphere-biosphere programme is being planned.

2. SOLAR SPECTRAL IRRADIANCES IN THE VISIBLE : BETWEEN 900 AND 400 NM.

In the 900 to 400 nm region, there are two different types of measurements of solar irradiance covering the whole range of the spectrum : those of Arvesen, Griffin and Pearsons (1969), and of Neckel and Labs (1984).

The spectral irradiance measurements by Arvesen et al. (1969) were made at an altitude of the order of 12 km during eleven data flights of about 3 hours. The wavelength intervals vary from 0.1 nm between 380 and 620 nm, 0.2 nm between 620 and 660 nm, 0.4 nm between 660 and 700 nm and 2 nm between 700 and 1000 nm. These different wavelength intervals provides an indication of the instrumental resolution ; it varies from 0.1 nm over most of the visible to 2 nm at the beginning of a region that is almost continuum. The uncertainty limits for these results depend on several factors and are related to the atmospheric transmittances : 0.90 at 400 nm, 0.94 at 500 nm, 0.97 at 700 nm and 0.99 at 900 nm for a vertical column. According to Arvesen et al. (1969) the uncertainty of their observational results cannot be more than 3%, depending particularly on the standard of spectral irradiance. These data were analyzed by Nicolet (1975) and his results are adopted, since a systematic error of the order of 2% has been estimated.

The last solar irradiances published by Neckel and Labs (1984) refer to 1 nm intervals, plotted in Fig. 1 from 330 nm to 630 nm, and to 2 nm intervals, shown in Fig. 2 from 630 to 870 nm. These irradiances are based on ground level observations made more than 10 years ago at the Jungfraujoch (3.6 km) at the centre of the solar disk, and recently adjusted with improved values of the centre-to-limb variations, so that a mean irradiance corresponding to the whole disk can be obtained as a basic solar spectral irradiance.

The results of these two determinations between 405 and 865 nm are shown for averaged over 10 nm spectra in Table 1. These numerical values agree with each other to ± 1% for more than 65% of the 47 intervals, to ± 2% for about 80%, and to ± 3% for more than 90% of the measurements. There is therefore an excellent, and even remarkable, agreement, between observational results obained by completely different methods. These comparisons are illustrated in Fig. 3 and 4 which indicate that, out of 47 values, 30 coincide (± 0%) and 42 lie within ± 3%; 2 are at + 4%, 2 at + 5% and 1 at - 6% at 415 nm.

Table 2 gives the spectral irradiances integrated over 5 nm intervals between 400 and 900 nm. They correspond to the values deduced by Nicolet (1975) and adopted as reference solar irradiance in Atmospheric Ozone 1985 : Assessment of our understanding of the processes controlling its present distribution and charge (WMO, 1985).

The detailed spectrum (0.1 nm for Arvesen et al., 1969, and 1 nm for Neckel and Labs, 1984) is illustrated in various figures, Fig. 5, 6, 7, 8, 9 and 10, between 610 and 400 nm for the spectral intervals 575-610 nm, 540-575 nm, 505-540 nm, 470-505 nm, 435-470 nm, and 400-435 nm, respectively. The corresponding numerical values for 1 nm intervals are given in Tables 3 and 4. Between 400 and 500 nm, the mean solar irradiance is obtained with a precision better than 2.5% for 95% of the 100 values. There are 5 exceptions, at 407-408 nmn 414-415 nm, 416-417 nm and 419-420 nm, respectively, where the differences may reach ± 6 ± 2%. Between 500 and 600 nm, the mean solar irradiance, also for

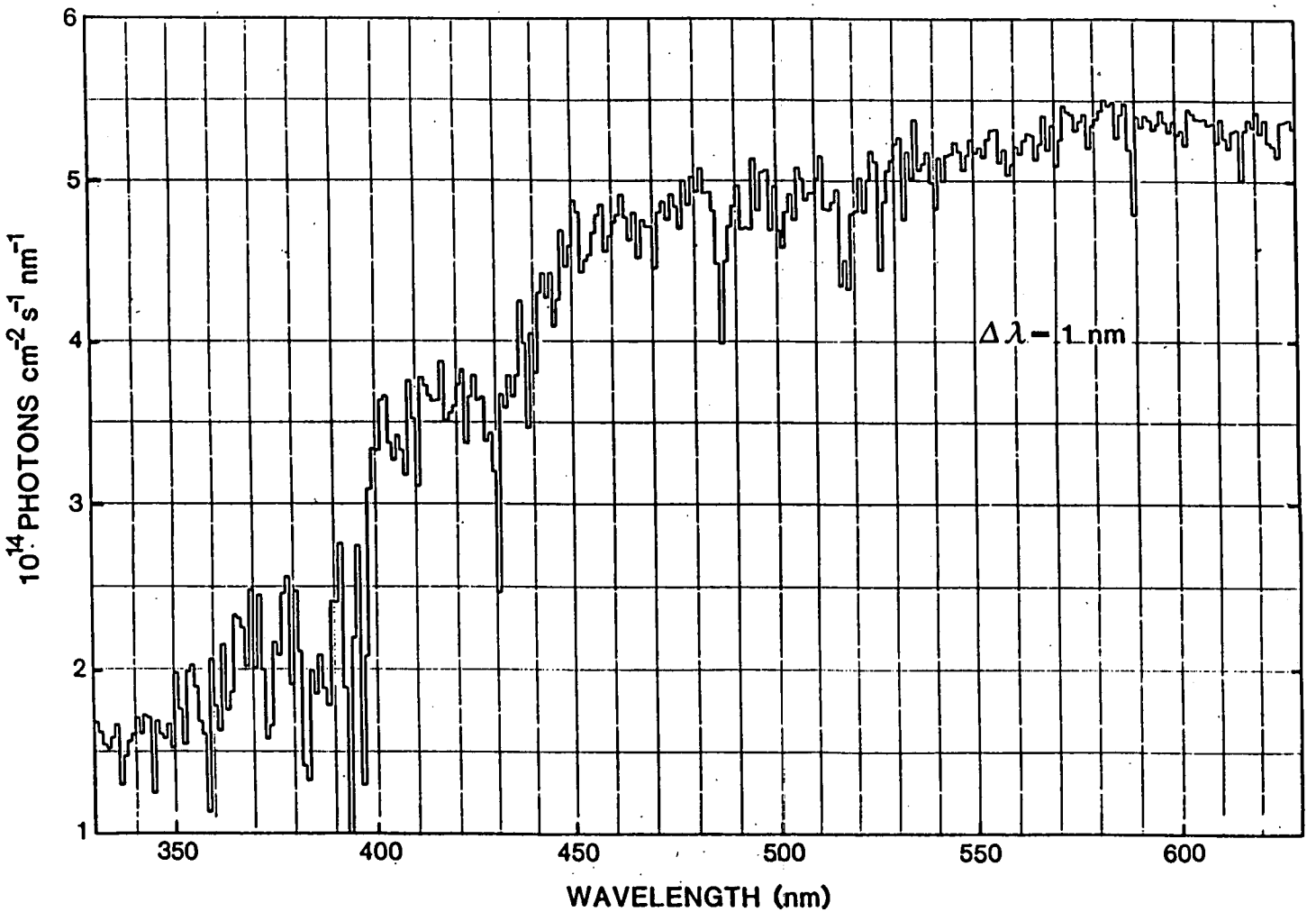

Fig. 1 - Solar spectral irradiances (photons cm^{-2} s^{-1}) in 1 nm intervals between 330 and 630 nm. From Neckel and Labs (1984).

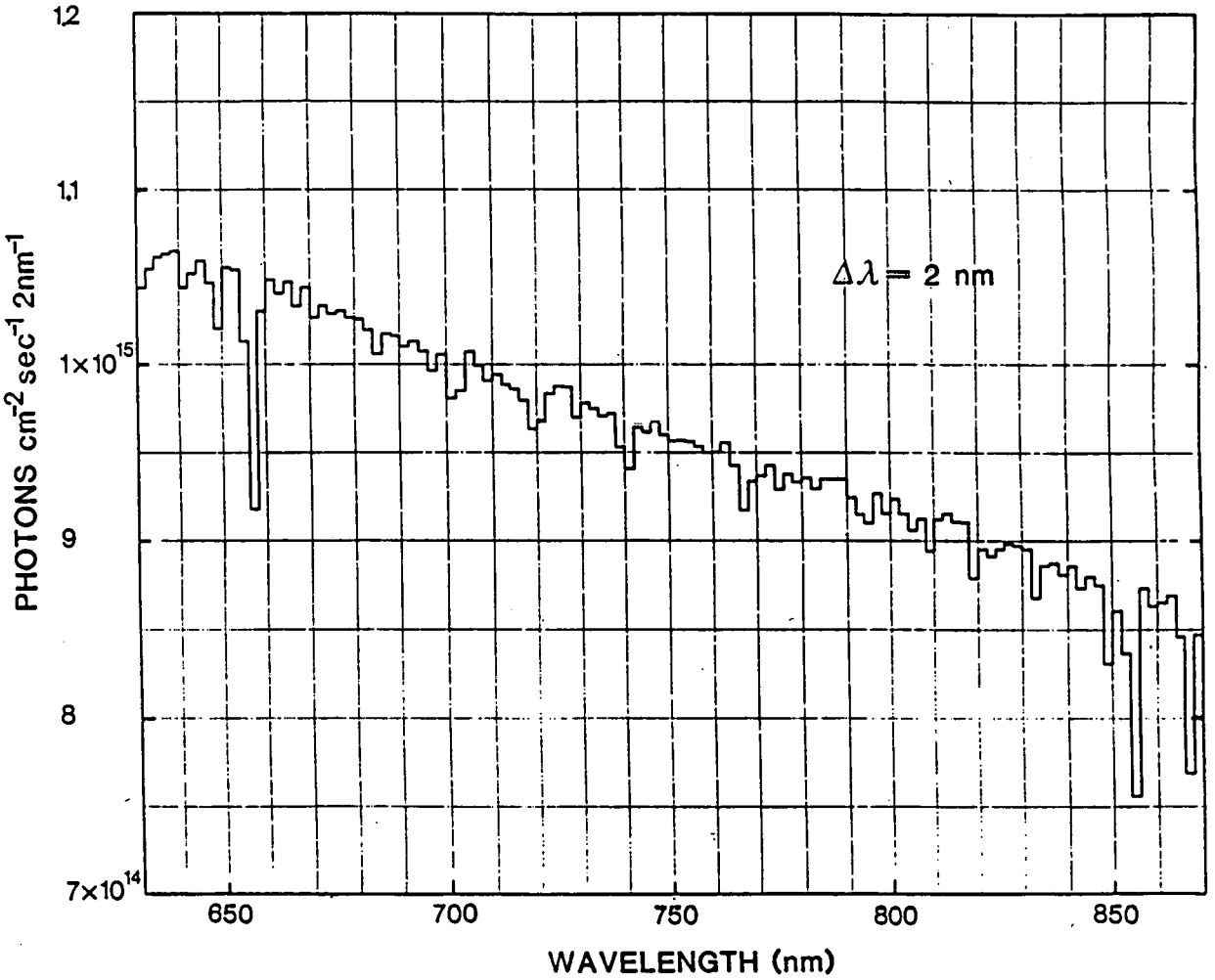

Fig. 2 - As Fig. 1, but in 2 nm intervals between 630 and 870 nm.

TABLE 1.- Solar spectral irradiances averaged in 10 nm intervals (10^{15} photons cm^{-2} s^{-1}) deduced from Arvesen et al. (1969) and adopted from Neckel and Labs (1984), from 400 to 900 nm.

λ + 5 nm	q_∞ cm^{-2} s^{-1} Neckel	q_∞ cm^{-2} s^{-1} Arvesen	Ratio	λ + 5 nm	q_∞ cm^{-2} s^{-1} Neckel	q_∞ cm^{-2} s^{-1} Arvesen	Ratio
405	3.45	3.53	0.98	645	5.22	5.14	1.02
415	3.61	3.84	0.94	655	5.07	5.07	1.00
425	3.57	3.68	0.97	665	5.21	5.24	0.99
435	3.67	3.73	0.98	675	5.15	5.23	0.98
445	4.33	4.39	0.99	685	5.09	5.12	0.99
455	4.67	4.70	0.99	695	5.03	5.17	0.97
465	4.73	4.76	0.99	705	4.96	5.05	0.98
475	4.82	4.91	0.98	715	4.91	4.96	0.99
485	4.72	4.73	1.00	725	4.90	4.93	0.99
495	4.88	4.89	1.00	735	4.85	4.88	0.99
505	4.86	4.87	1.00	745	4.79	4.78	1.00
515	4.76	4.72	1.01	755	4.77	4.79	1.00
525	4.94	4.90	1.01	765	4.70	4.70	1.00
535	5.11	5.07	1.01	775	4.68	4.62	1.01
545	5.12	5.04	1.01	785	4.67	4.67	1.00
555	5.19	5.05	1.03	795	4.59	4.56	1.01
565	5.25	5.11	1.03	805	4.55	4.50	1.01
575	5.33	5.30	1.01	815	4.53	4.39	1.03
585	5.34	5.29	1.01	825	4.48	4.34	1.03
595	5.37	5.36	1.00	835	4.48	4.27	1.05
605	5.36	5.33	1.01	845	4.34	4.19	1.04
615	5.28	5.26	1.00	855	4.19	3.99	1.05
625	5.32	5.26	1.01	865	4.19	4.01	1.04
635	5.29	5.28	1.00	875		4.08	
				885		4.02	
				895		3.99	

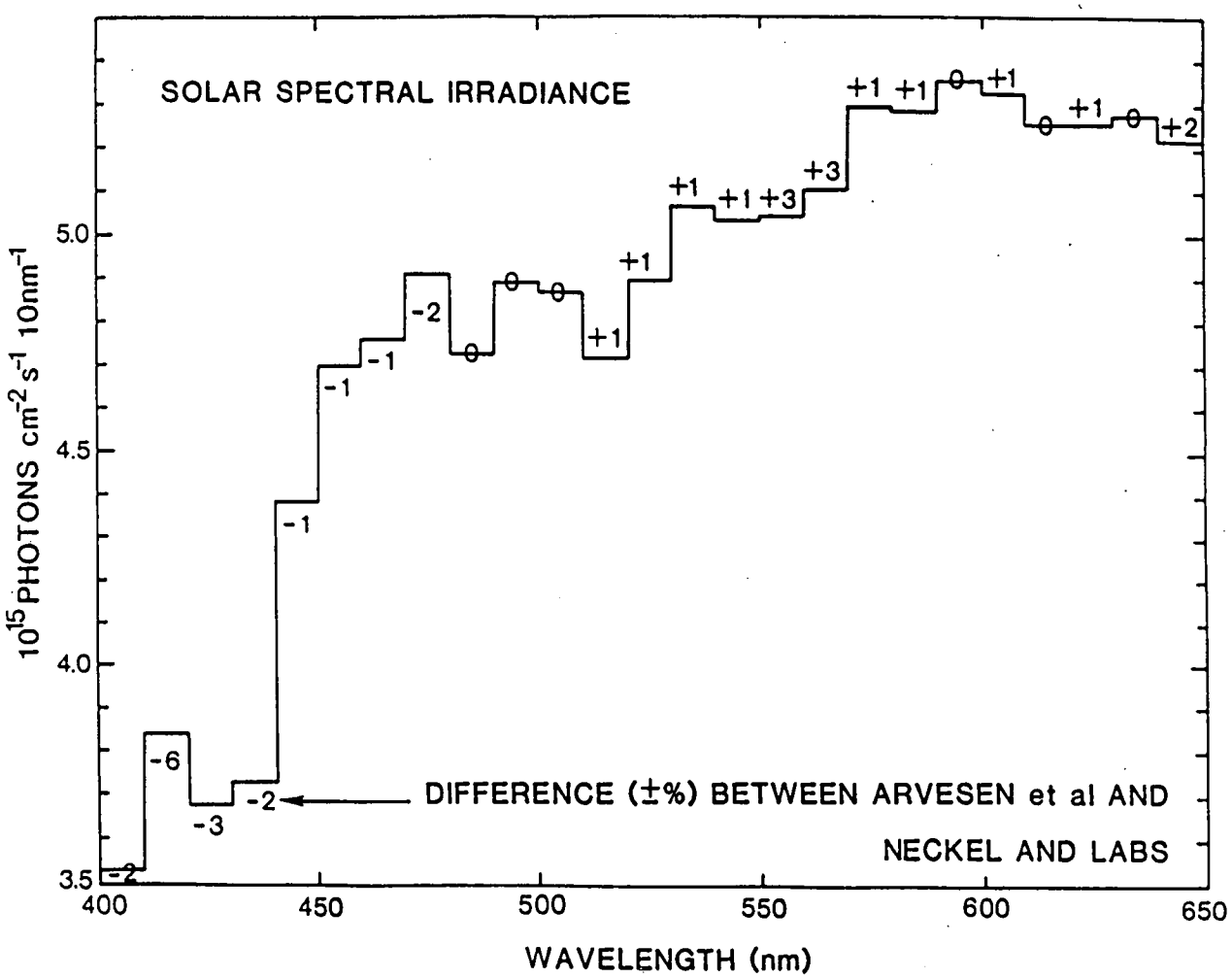

Fig. 3 - Solar spectral irradiances (photons cm^{-2} s^{-1} 10 nm^{-1}) from 400 to 650 nm. Differences (± %) between values deduced from Arvesen et al. 1969) and values obtained from Neckel and Labs (1984) are shown.

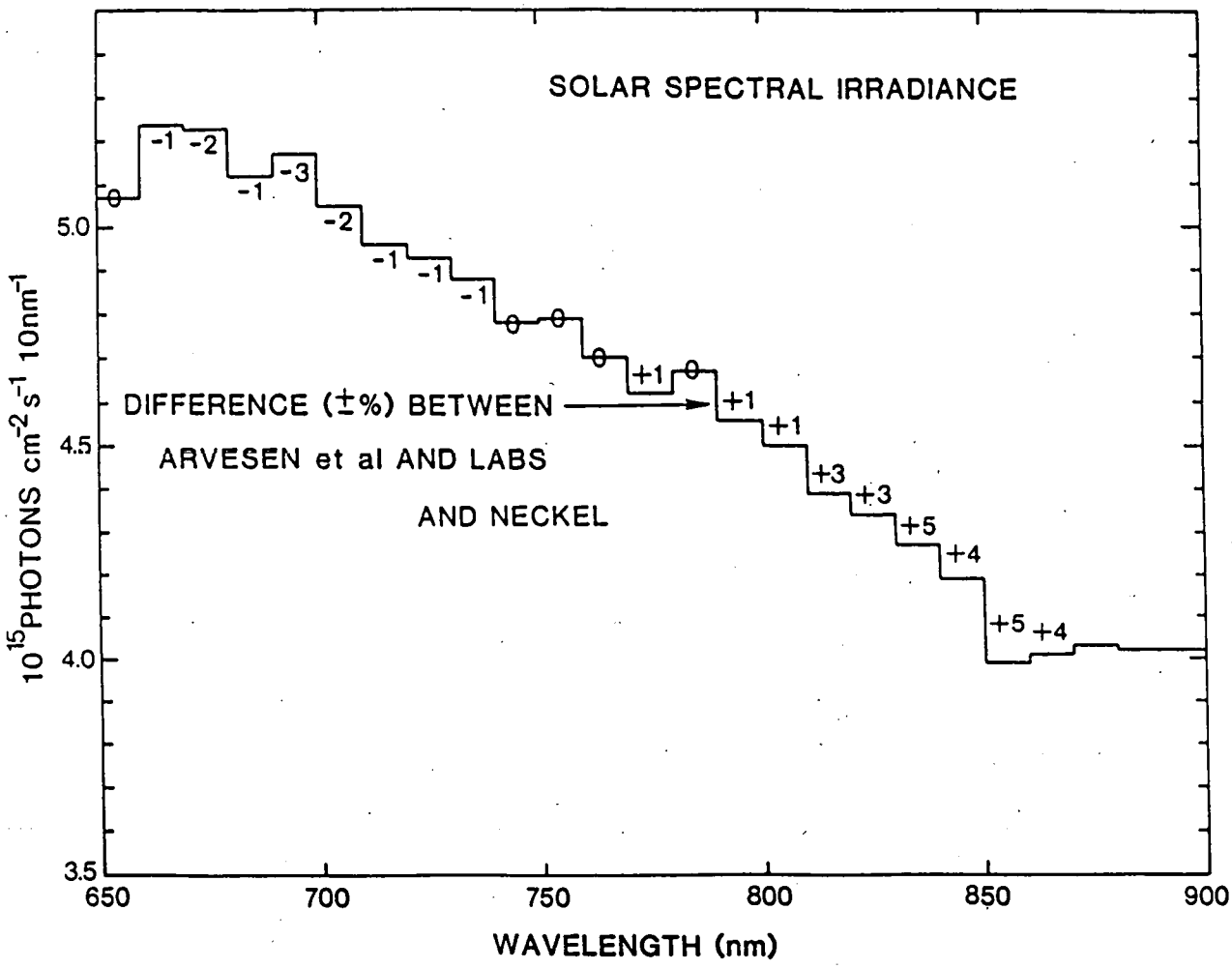

Fig. 4 - Solar spectral irradiances (photons cm^{-2} s^{-1} nm^{-1}) from 650 to 900 nm. Identical to Fig. 3.

TABLE 2.- Solar spectral irradiances averaged in 5 nm intervals (10^{15} photons cm^{-2} s^{-1}) from 400 nm to 900 nm.

λ ± 2.5 nm	q_∞ $cm^{-2}s^{-1}$	λ ± 2.5 nm	q_∞ $cm^{-2}s^{-1}$	λ ± 2.5 nm	q_∞ $cm^{-2}s^{-1}$	λ ± 2.5 nm	q_∞ $cm^{-2}s^{-1}$	λ ± 2.5 nm	q_∞ $cm^{-2}s^{-1}$
400	1.69	500	2.40	600	2.63	700	2.58	800	2.27
405	1.70	505	2.46	605	2.68	705	2.52	805	2.27
410	1.84	510	2.49	610	2.66	710	2.51	810	2.20
415	1.87	515	2.32	615	2.59	715	2.48	815	2.22
420	1.95	520	2.39	620	2.69	720	2.45	820	2.18
425	1.81	525	2.42	625	2.61	725	2.48	825	2.20
430	1.67	530	2.55	630	2.62	730	2.45	830	2.14
435	1.98	535	2.51	635	2.62	735	2.44	835	2.14
440	2.02	540	2.49	640	2.63	740	2.39	840	2.13
445	2.18	545	2.55	645	2.60	745	2.40	845	2.09
450	2.36	550	2.53	650	2.55	750	2.41	850	2.05
455	2.31	555	2.54	655	2.48	755	2.40	855	1.95
460	2.39	560	2.50	660	2.57	760	2.38	860	2.07
465	2.38	565	2.57	665	2.61	765	2.34	865	1.95
470	2.39	570	2.58	670	2.61	770	2.32	870	2.04
475	2.44	575	2.67	675	2.62	775	2.30	875	2.04
480	2.51	580	2.67	680	2.62	780	2.33	880	2.01
485	2.30	585	2.70	685	2.57	785	2.34	885	2.02
490	2.39	590	2.62	690	2.52	790	2.29	890	2.01
495	2.48	595	2.69	695	2.60	795	2.29	895	2.01

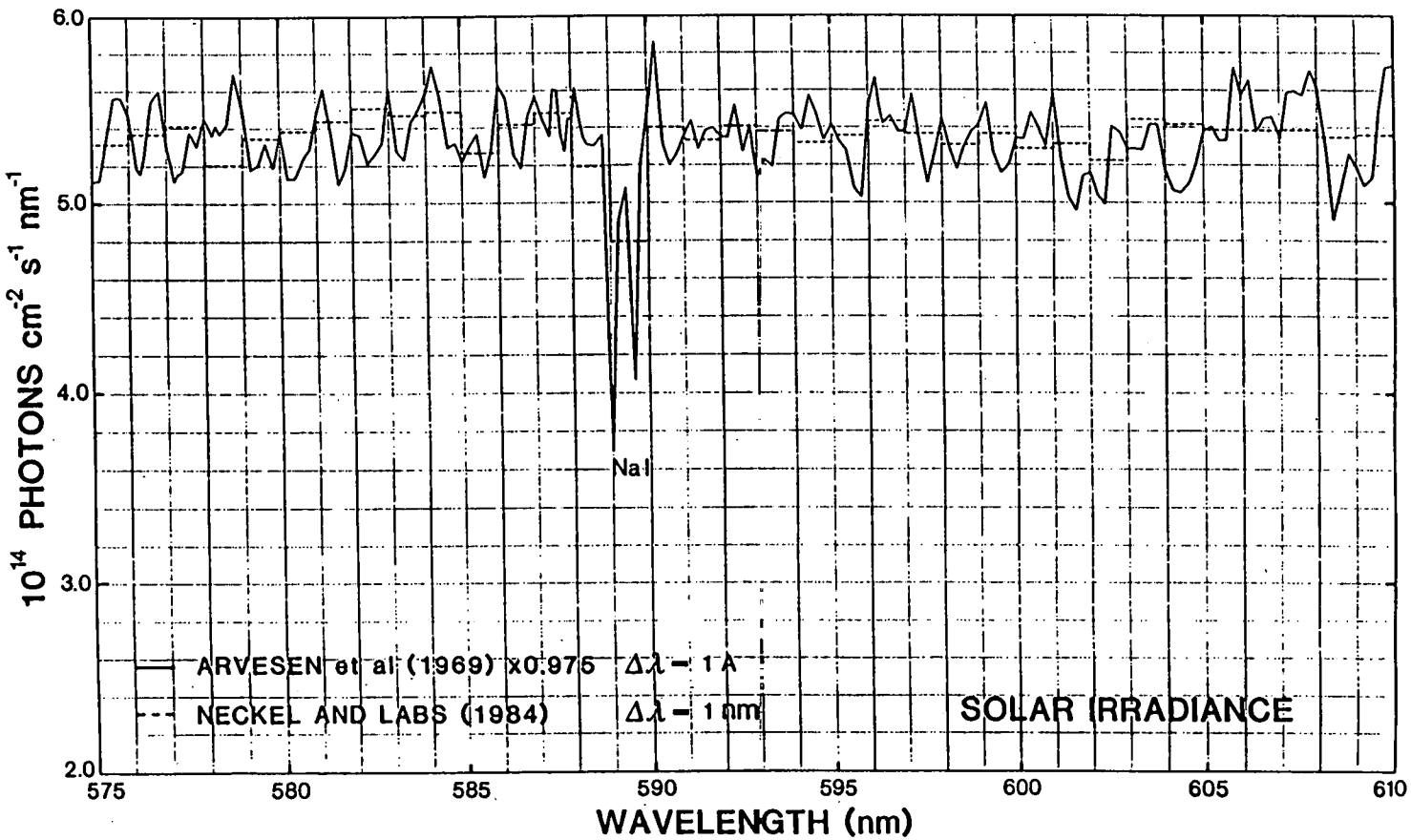

Fig. 5 - Solar spectral irradiances (photons cm^{-2} s^{-1} nm^{-1}) deduced from Arvesen et al. (1969) for 0.1 nm and obtained from Neckel and Labs (1984) for 1 nm.

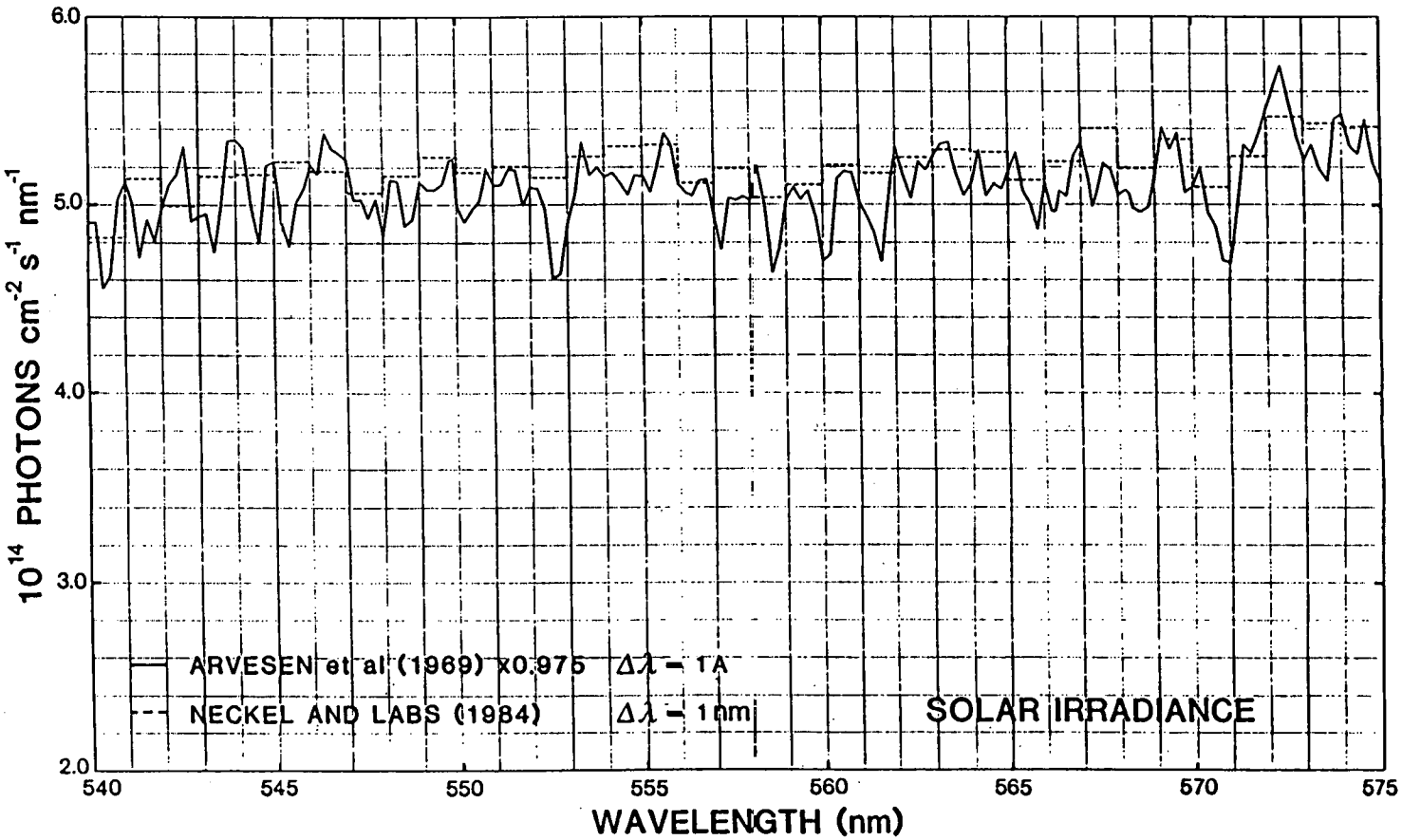
6.0
5.0
4.0
3.0
2.0
10^{14} PHOTONS cm^{-2} s^{-1} nm^{-1}
ARVESEN et al (1969) x0.975 Δλ = 1A
NECKEL AND LABS (1984) Δλ = 1nm
SOLAR IRRADIANCE
540
545
550
555
560
565
570
575
WAVELENGTH (nm)

Fig. 6 - As Fig. 5.

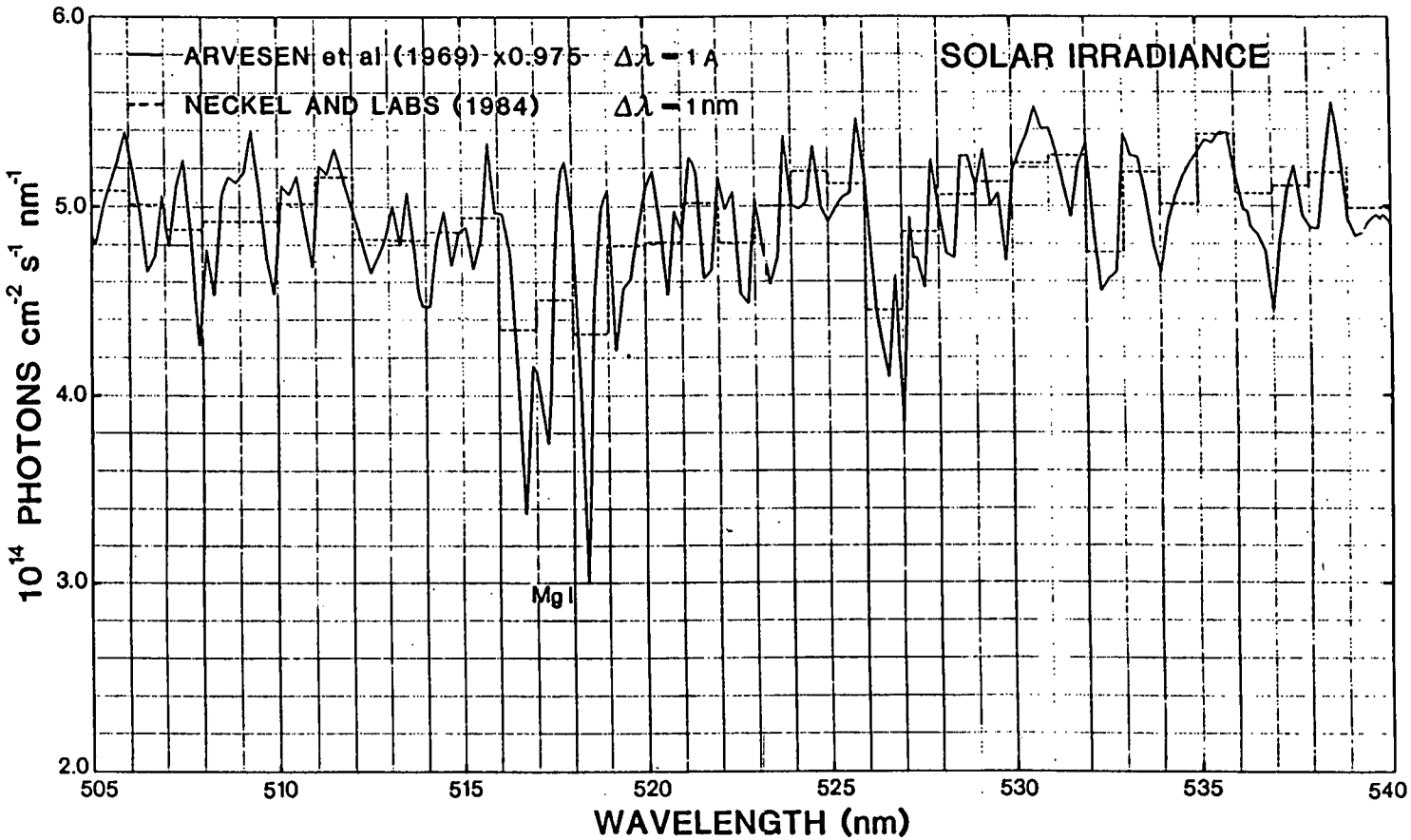

Fig. 7 - As Fig. 5 and 6.

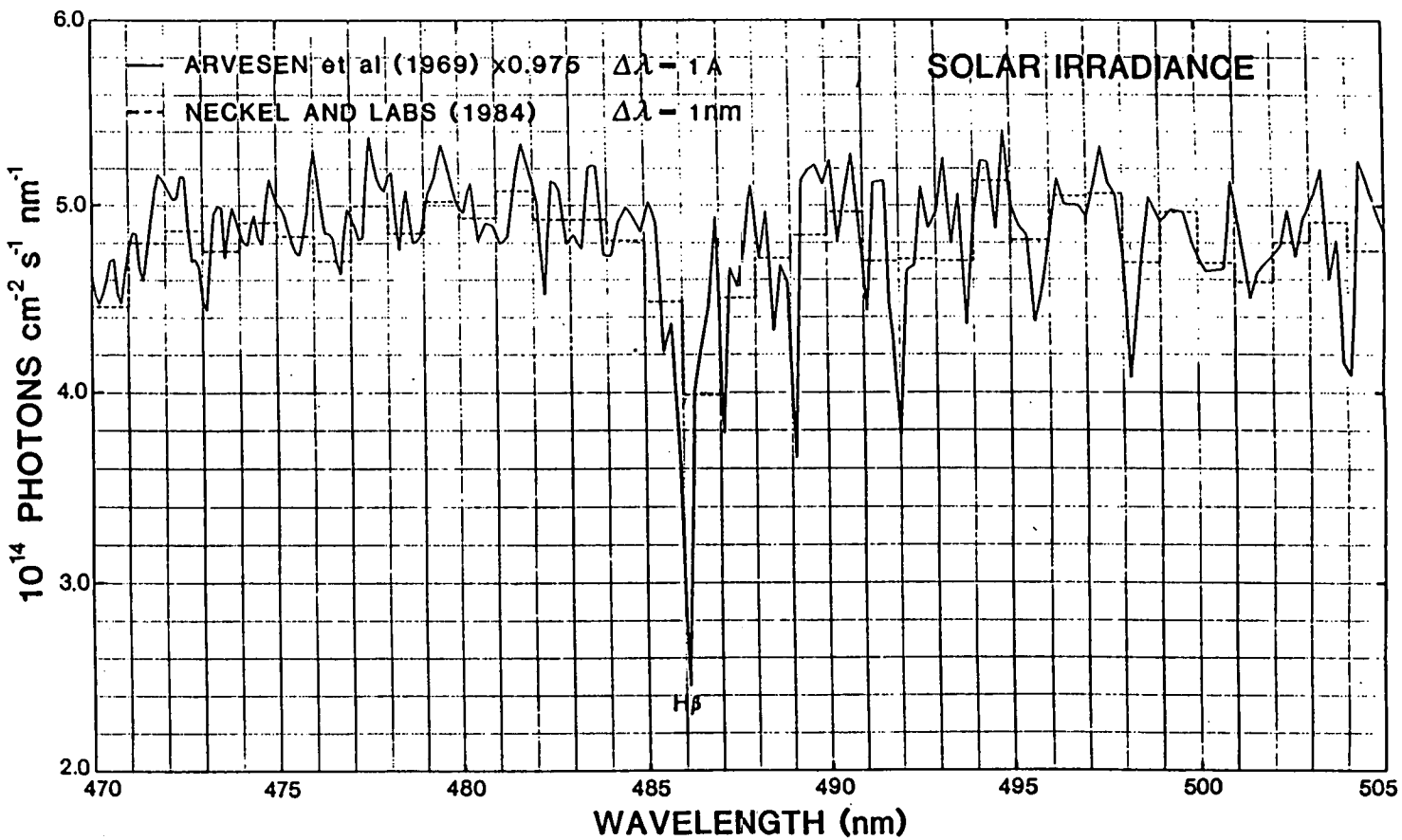

Fig. 8 - As Fig. 5-7.

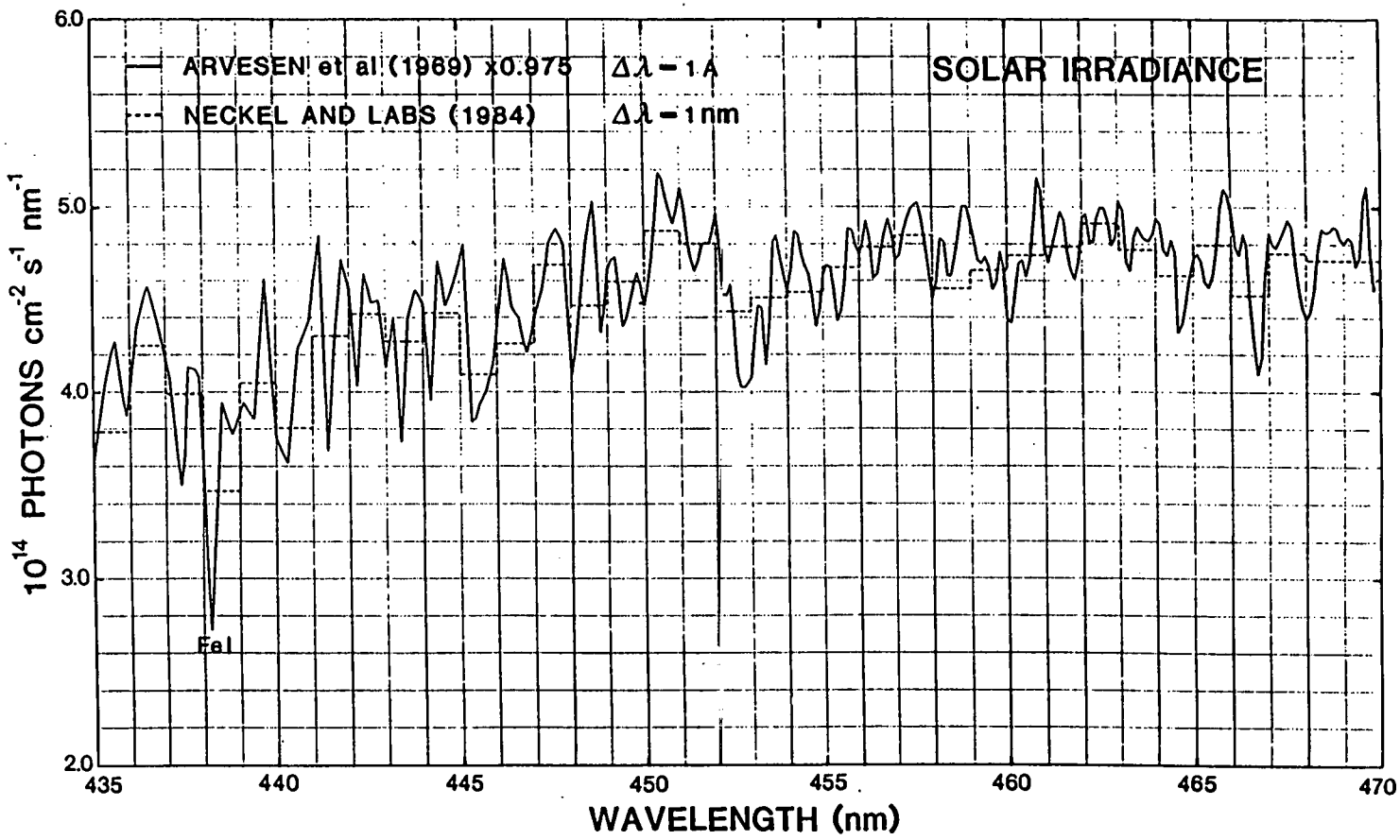

Fig. 9 - As Fig. 5-8.

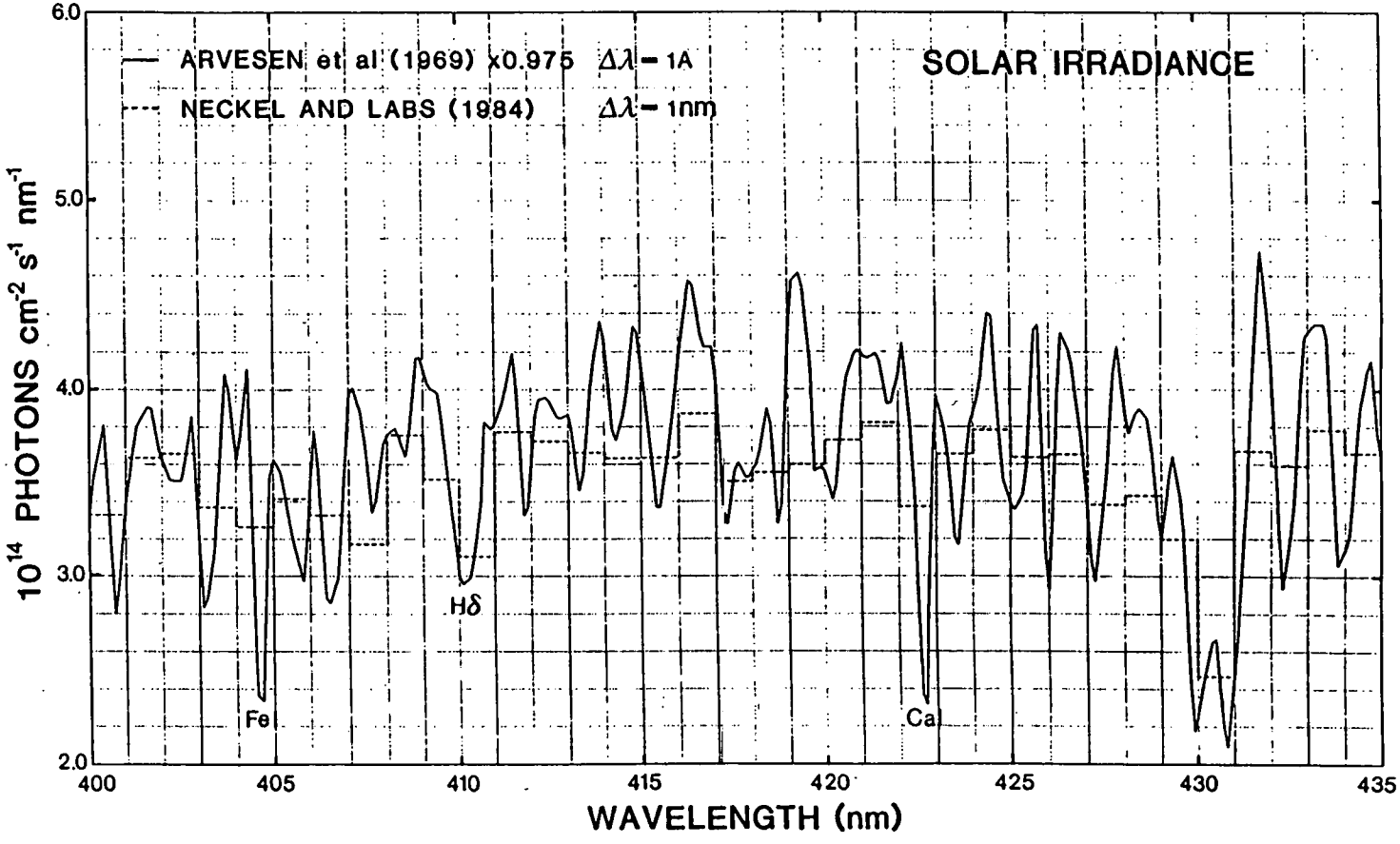

Fig. 10 - As Fig. 5-9.

TABLE 3.- Solar spectral irradiances averaged in 1 nm intervals, $q_\infty = 10^{14}$ photons cm^{-2} s^{-1}; mean values as deduced from Arvesen et al. (1969) and adopted from Neckel and Labs (1984) between 400 and 500 nm.

Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)
400-401	3.35	425-426	3.64	450-451	4.90	475-476	4.88
1 2	3.69	6 7	3.77	1 2	4.81	6 7	4.80
2 3	3.62	7 8	3.49	2 3	4.39	7 8	5.03
3 4	3.40	8 9	3.57	3 4	4.51	8 9	4.89
4 5	3.25	429-430	3.15	4 5	4.58	479-480	5.08
5 6	3.36	430-431	3.44	5 6	4.67	480-481	4.94
6 7	3.31	1 2	3.74	6 7	4.79	1 2	5.07
7 8	3.43	2 3	3.58	7 8	4.85	2 3	4.92
8 9	3.81	3 4	3.83	8 9	4.67	3 4	4.94
409-410	3.62	4 5	3.71	459-460	4.67	4 5	4.85
410-411	3.23	5 6	3.89	460-461	4.74	5 6	4.44
1 2	3.79	6 7	4.31	1 2	4.79	6 7	4.01
2 3	3.80	7 8	3.95	2 3	4.91	7 8	4.55
3 4	3.78	8 9	3.51	3 4	4.80	8 9	4.68
4 5	3.83	439-440	4.06	4 5	4.65	489-490	4.87
5 6	3.67	440-441	3.92	5 6	4.80	490-491	5.00
6 7	4.11	1 2	4.36	6 7	4.55	1 2	4.69
7 8	3.52	2 3	4.41	7 8	4.75	2 3	4.72
8 9	3.62	3 4	4.27	8 9	4.73	3 4	4.79
419-420	3.87	4 5	4.44	469-470	4.75	4 5	5.14
420-421	3.78	5 6	4.12	470-471	4.52	5 6	4.79
1 2	3.96	6 7	4.35	1 2	4.85	6 7	5.03
2 3	3.37	7 8	4.67	2 3	4.89	7 8	5.08
3 4	3.63	8 9	4.53	3 4	4.80	8 9	4.68
424-425	3.86	449-450	4.57	474-475	4.91	499-500	4.94

TABLE 4.- Solar spectral irradiances averaged in 1 nm intervals, $q_\infty = 10^{14}$ photons cm^{-2} s^{-1}; mean values as deduced from Arvesen et al. (1969) and adopted from Neckel and Labs (1984) between 500 and 600 nm.

Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)
500-501	4.72	525-526	5.12	550-551	5.10	575-576	5.35
1 2	4.64	6 7	4.44	1 2	5.16	6 7	5.38
2 3	4.83	7 8	4.82	2 3	5.01	7 8	5.34
3 4	4.84	8 9	5.04	3 4	5.20	8 9	5.34
4 5	4.82	529-530	5.09	4 5	5.22	579-580	5.31
5 6	5.19	530-531	5.30	5 6	5.27	580-581	5.31
6 7	4.95	1 2	5.23	6 7	5.10	1 2	5.39
7 8	4.87	2 3	4.78	7 8	5.11	2 3	5.42
8 9	4.92	3 4	5.13	8 9	4.97	3 4	5.44
509-510	4.96	4 5	5.03	559-560	5.05	4 5	5.47
510-511	5.01	5 6	5.35	560-561	5.11	5 6	5.28
1 2	5.16	6 7	4.97	1 2	5.05	6 7	5.41
2 3	4.81	7 8	5.03	2 3	5.21	7 8	5.46
3 4	4.82	8 9	5.17	3 4	5.25	8 9	5.21
4 5	4.81	539-540	4.95	4 5	5.21	589-590	4.78
5 6	4.94	540-541	4.83	5 6	5.10	590-591	5.41
6 7	4.31	1 2	5.02	6 7	5.16	1 2	5.35
7 8	4.52	2 3	5.04	7 8	5.27	2 3	5.38
8 9	4.32	3 4	5.08	8 9	5.11	3 4	5.35
519-520	4.73	4 5	5.14	569-570	5.30	4 5	5.38
520-521	4.86	5 6	5.11	570-571	5.02	5 6	5.29
1 2	4.98	6 7	5.23	1 2	5.24	6 7	5.45
2 3	4.82	7 8	5.04	2 3	5.50	7 8	5.35
3 4	4.95	8 9	5.08	3 4	5.36	8 9	5.31
524-525	5.12	549-550	5.19	574-575	5.36	599-600	5.33

1 nm intervals, is always obained with a precision better than 2.5% for the values. Finally, Table 5 provides solar spectral irradiances in 1 nm intervals between 600 and 900 nm as deduced by Nicolet (1975) from the adjusted data published by Arvesen et al. (1969).

In studies of the atmospheric photolysis of ozone in the region of the Chappuis bands, one can adopt an interval of 50 nm; the practical values are listed in Table 6 which also includes the corresponding absorption cross-sections for molecular scattering and ozone.

Thus, in the 400-900 nm spectral range, the listing of solar irradiances for such intervals such as 10 nm, 5 nm and 1 nm, derived as they are from measurements by two completely different methods, indicate that the spread is relatively small, and that at present the uncertainty is associated with the absolute accuracy of any measurement of the radiation from the entire solar disk.

3. SOLAR SPECTRAL IRRADIANCES IN THE ULTRAVIOLET : BETWEEN 400 AND 300 NM

In the whole region between 300 and 400 nm, there are four main types of detailed measurements of the solar spectral irradiances. The last results were obtained in 1985 in Spacelab 2 by VanHoosier et al. (1987) : the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM). These results, obtained with a 0.15 nm band pass, are listed at each 0.05 nm. Satellite data were also obtained in 1978 by Heath (1980); for them the spectral irradiances are listed at intervals of 0.2 nm for an instrumental resolution of about 1 nm. The irradiances deduced from ground level observations (as explained before) by Neckel and Labs (1984) refer to 1 nm intervals between 330 and 400 nm. The observational data of Arvesen et al. (1969) obtained by aircraft at about 12 km were published for intervals of 0.1 nm between 380 and 400 nm, 0.2 nm between 380 and 340 nm and 0.4 nm between 340 and 300 nm. These observed irradiances must be adjusted (see Nicolet, 1975) to a slightly different value of the total irradiance and, at the same time, to a difference in wavelength

TABLE 5.- Solar spectral irradiances averaged in 1 nm intervals, $q_\infty = 10^{14}$ photons cm^{-2} s^{-1}, deduced from Arvesen et al. (1969).

Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)
600-601	5.40	650-651	5.17	700-701	5.12
601-602	5.15	651-652	5.28	701-702	5.08
602-603	5.27	652-653	5.19	702-703	5.08
603-604	5.33	653-654	5.38	703-704	5.09
604-605	5.14	654-655	5.13	704-705	5.08
605-606	5.46	655-656	4.75	705-706	5.04
606-607	5.48	656-657	4.47	706-707	5.01
607-608	5.59	657-658	5.03	707-708	4.98
608-609	5.19	658-659	5.16	708-709	4.99
609-610	5.38	659-660	5.13	709-710	5.04
610-611	5.38	660-661	5.22	710-711	5.06
611-612	5.26	661-662	5.23	711-712	5.04
612-613	5.23	662-663	5.21	712-713	5.02
613-614	5.09	663-664	5.27	713-714	4.99
614-615	5.28	664-665	5.20	714-715	4.97
615-616	5.21	665-666	5.33	715-716	4.95
616-617	5.01	666-667	5.18	716-717	4.93
617-618	5.28	667-668	5.29	717-718	4.92
618-619	5.34	668-669	5.23	718-719	4.89
619-620	5.53	669-670	5.27	719-720	4.85
620-621	5.33	670-671	5.26	720-721	4.86
621-622	5.40	671-672	5.14	721-722	4.92
622-623	5.25	672-673	5.05	722-723	4.96
623-624	5.18	673-674	5.22	723-724	4.98
624-625	5.02	674-675	5.42	724-725	4.99
625-626	5.27	675-676	5.27	725-726	4.97
626-627	5.45	676-677	5.20	726-727	4.94
627-628	5.27	677-678	5.32	727-728	4.90
628-629	5.23	678-679	5.18	728-729	4.89
629-630	5.27	679-680	5.25	729-730	4.89
630-631	5.16	680-681	5.27	730-731	4.90
631-632	5.18	681-682	5.22	731-732	4.89
632-633	5.45	682-683	5.19	732-733	4.89
633-634	5.16	683-684	5.25	733-734	4.89
634-635	5.27	684-685	5.15	734-735	4.90
635-636	5.11	685-686	5.16	735-736	4.92
636-637	5.30	686-687	5.05	736-737	4.90
637-638	5.35	687-688	4.92	737-738	4.85
638-639	5.49	688-689	4.93	738-739	4.81
639-640	5.29	689-690	5.08	739-740	4.79
640-641	5.08	690-691	5.16	740-741	4.77
641-642	5.14	691-692	5.08	741-742	4.75
642-643	5.28	692-693	5.10	742-743	4.75
643-644	5.17	693-694	5.13	743-744	4.76
644-645	5.18	694-695	5.26	744-745	4.77
645-646	5.34	695-696	5.21	745-746	4.78
646-647	5.17	696-697	5.16	746-747	4.80
647-648	5.13	697-698	5.32	747-748	4.81
648-649	5.06	698-699	5.27	748-749	4.82
649-650	4.77	699-700	5.04	749-750	4.82

TABLE 5.- (followed)

Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)	Wavelength Interval (nm)	q_∞ (1 nm)
750-751	4.80	800-801	4.53	850-851	4.06
751-752	4.79	801-802	4.53	851-852	4.05
752-753	4.79	802-803	4.53	852-853	3.95
753-754	4.80	803-804	4.53	853-854	3.76
754-755	4.80	804-805	4.53	854-855	3.75
755-756	4.80	805-806	4.52	855-856	3.90
756-757	4.80	806-807	4.50	856-857	4.03
757-758	4.78	807-808	4.46	857-858	4.13
758-759	4.76	808-809	4.43	858-859	4.16
759-760	4.74	809-810	4.40	859-860	4.11
760-761	4.74	810-811	4.39	860-861	4.11
761-762	4.75	811-812	4.39	861-862	4.15
762-763	4.74	812-813	4.41	862-863	4.10
763-764	4.72	813-814	4.45	863-864	3.97
764-765	4.70	814-815	4.45	864-865	3.87
765-766	4.70	815-816	4.39	865-866	3.80
766-767	4.69	816-817	4.36	866-867	3.85
767-768	4.67	817-818	4.36	867-868	4.02
768-769	4.65	818-819	4.36	868-869	4.10
769-770	4.64	819-820	4.35	869-870	4.10
770-771	4.63	820-821	4.33	870-871	4.09
771-772	4.62	821-822	4.30	871-872	4.08
772-773	4.61	822-823	4.31	872-873	4.08
773-774	4.62	823-824	4.35	873-874	4.09
774-775	4.60	824-825	4.37	874-875	4.10
775-776	4.57	825-826	4.37	875-876	4.11
776-777	4.58	826-827	4.36	876-877	4.10
777-778	4.63	827-828	4.35	877-878	4.05
778-779	4.66	828-829	4.32	878-879	4.03
779-780	4.67	829-830	4.27	879-880	4.03
780-781	4.68	830-831	4.27	880-881	4.03
781-782	4.67	831-832	4.30	881-882	4.01
782-783	4.67	832-833	4.30	882-883	4.01
783-784	4.68	833-834	4.27	883-884	4.05
784-785	4.68	834-835	4.24	884-885	4.05
785-786	4.68	835-836	4.22	885-886	4.02
786-787	4.67	836-837	4.24	886-887	4.01
787-788	4.66	837-838	4.29	887-888	4.02
788-789	4.64	838-839	4.29	888-889	4.02
789-790	4.61	839-840	4.25	889-890	4.02
790-791	4.57	840-841	4.24	890-891	4.01
791-792	4.53	841-842	4.25	891-892	4.00
792-793	4.53	842-843	4.23	892-893	3.99
793-794	4.57	843-844	4.17	893-894	4.00
794-795	4.58	844-845	4.15	894-895	4.02
795-796	4.58	845-846	4.18	895-896	4.03
796-797	4.57	846-847	4.20	896-897	4.02
797-798	4.56	847-848	4.21	897-898	3.96
798-799	4.55	848-849	4.18	898-899	3.95
799-800	4.54	849-850	4.11	899-900	3.94

TABLE 6.- Solar spectral irradiances (photons cm^{-2} s^{-1}) at 1 A.U. averaged in 50 nm intervals with the corresponding molecular scattering and O_3 absorption cross sections for the Chappuis bands between 400 nm and 850 nm. Photodissociation frequencies (s^{-1}) are also given.

λ (A)	photons ($cm^{-2}s^{-1}$)	Scattering (cm^2)	O_3 absorption (cm^2)	$J_\infty(O_3)$ (s^{-1})	%
400	1.47×10^{16}	1.67×10^{-26}			
450	2.18	1.03	2.34×10^{-22}	5.11×10^{-6}	1.49
500	2.40	6.66×10^{-27}	1.25×10^{-21}	2.99×10^{-5}	8.72
550	2.56	4.51	3.39	8.66	25.27
600	2.66	3.17	4.46	1.18×10^{-4}	34.56
650	2.59	2.29	2.47	6.40×10^{-5}	18.69
700	2.54	1.70	9.75×10^{-22}	2.48	7.24
750	2.39	1.28	3.85	9.21×10^{-6}	2.69
800	2.26	9.88×10^{-28}	2.05	4.63	1.35
850	2.07	7.74×10^{-28}			

which rises to 0.4 nm at wavelengths less than 340 nm (see, for example, Broadfoot 1972). It is important to remember that the results depend on the atmospheric transmittance which was determined at 11.5 km; if it is still 0.9 at 400 nm for a vertical column, it decreases to 0.8 at 330 nm and it is only 0.45 at 310 nm. According to Arvesen et al. (1969) the maximum instrumental error of 3% at 400 nm increases to 4% at 330 nm and reaches at least 7% at 310 nm.

A first comparison of the various results obtained by these four different methods of measurement can be made for spectral intervals of 10 nm. The numerical results are presented in Table 7 where the reference spectrum is based on the results obtained by SUSIM. The values of the various ratios which are indicated in this table depend on the wavelength and on the observational techniques used. Between 350 and 400 nm, there is a systematic difference of + 15 ± 5% between the SUSIM irradiances and the other data. The irradiances deduced from Arvesen et al., Heath, and Neckel and Labs are practically in agreement : 0 ± 3%. Between 330 and 350 nm, our analysis shows clearly that the ratio SUSIM/ARVESEN is 1.00 ± 0.01 and that the ratio SUSIM/HEATH reaches 1.04 ± 0.01. The data of Neckel and Labs should not be considered at wavelengths less than 350 nm. Finally, the spectral irradiances deduced from the observational data obtained by Heath at wavelengths shorter than 330 nm are 8 ± 1% less than the irradiances deduced from SUSIM; a more detailed analysis is required in this region of the spectrum. The large differences in irradiance distributions below 350 nm must be attributed to difficulties besetting the various types of measurements.

For easy comparison with earlier work the data are presented at 5 nm intervals in Table 8. The various differences detected in 10 nm intervals are more apparent. Between 350 and 400 nm, the SUSIM irradiances are higher (5% near 350 nm to 15% near 375) than the other irradiances. Between 350 nm and 325 nm, the comparison made between the irradiances deduced from the observational data of Arvesen et al. and of Heath are in agreement with the SUSIM data, since the differences over this wavelength range are between 0 and 5%. Thus, the SUSIM data can be

TABLE 7.-Solar spectral irradiances averaged in 10 nm intervals, $q_\infty = 10^{15}$ photons cm^{-2} s^{-1}, deduced from Spacelab 2 measurements (SUSIM) between 400 nm and 300 nm and compared with results deduced from observations of Heath, of Arvesen et al. and of Neckel and Labs.

Wavelength Interval (nm)	q_∞ SUSIM	Ratio SUSIM HEATH	Ratio SUSIM ARVESEN	Ratio SUSIM NECKEL	Ratio ARVESEN HEATH	Ratio ARVESEN NECKEL	Ratio HEATH NECKEL
400-390	2.66	1.16	1.13	1.17	1.03	1.03	1.00
390-380	2.31	1.19	1.16	1.20	1.03	1.03	1.00
380-370	2.50	1.17	1.21	1.20	0.97	0.99	1.02
370-360	2.31	1.13	1.12	1.12	1.01	1.00	0.99
360-350	1.94	1.10	1.09	1.10	1.01	1.01	0.99
350-340	1.73	1.05	1.01	1.08	1.04	1.07	1.03
340-330	1.66	1.03	0.99	1.07	1.04	1.08	1.04
330-320	1.51	1.08	1.05	-	1.03		
320-310	1.20	1.09	1.04	-	1.04		
310-300	0.93	1.07	1.05	-	1.02		

TABLE 8.-Solar spectral irradiances averaged in 5 nm intervals, $q_\infty = 10^{14}$ photons cm^{-2} s^{-1}, deduced from Spacelab 2 measurements (SUSIM) between 400 nm and 300 nm and compared with results deduced from observations of Heath, of Arvesen et al. and of Neckel and Labs.

Wavelength Interval (nm)	q_∞ SUSIM	Ratio HEATH SUSIM	Ratio ARVESEN SUSIM	Ratio NECKEL SUSIM	Ratio NECKEL ARVESEN	Ratio NECKEL HEATH
400-395	14.53	0.87	0.89	0.86	0.97	0.99
395-390	12.06	0.85	0.88	0.85	0.96	0.99
390-385	11.72	0.86	0.91	0.86	0.95	0.99
385-380	11.43	0.81	0.82	0.81	0.99	1.00
380-375	13.52	0.83	0.84	0.83	0.98	0.99
375-370	11.44	0.87	0.81	0.85	1.04	0.97
370-365	13.03	0.86	0.89	0.87	0.98	1.01
365-360	10.09	0.92	0.90	0.91	1.01	0.99
360-355	9.44	0.89	0.88	0.94	1.01	1.00
355-350	9.12	0.93	0.95	0.94	0.98	1.01
350-345	8.63	0.95	0.98	0.93	0.95	0.98
345-340	8.64	0.96	1.00	0.92	0.93	0.97
340-335	8.14	0.96	1.00	0.93	0.94	0.97
335-330	8.42	0.98	1.02	0.94	0.93	0.96
330-325	8.53	0.95	1.00			
325-320	6.55	1.08	(0.90)			
320-315	6.02	0.93	(0.98)			
315-310	6.00	0.91	(0.93)			
310-305	5.06	0.91	(0.90)			
305-300	4.23	0.96	(1.02)			

used at higher resolution. For the wavelength range below 325 nm, another analysis is required with better resolution (at least 1 nm intervals), and also with other solar irradiance observations.

In order to adopt spectral irradiances at wavelengths less than 400 nm for intervals of the order of 1 nm, it is necessary to keep in mind the various parameters which are involved in the determination of the solar intensity distribution only on a relative scale, and then in the transformation to an absolute calibration by adjustment of the energy scale. Thus, the atmospheric transmittance must be taken into account for observations made in the atmosphere; the spectral resolution is different for each observational result; the summations made for intervals of 1 nm are not identical; the inaccuracy of the wavelengths used in the calculations is not always known and may be variable; the differences between the wavelengths in vacuum and in the air (0.1 nm at 350 nm) are often forgotten. In other words, several factors playing an undetermined role prevent the possibility of fixing the systematic errors and those usually encountered with data obtained with instruments of different resolving powers. The absolute accuracy and the relative precision of different experimental solar spectral irradiances are determined only by comparison.

The values of the spectral irradiances from 330 to 400 nm integrated over a 1 nm interval from Arvesen et al. (1969) and from Neckel and Labs (1984), are compared in Fig. 11 and 12 with the values obtained by Heath (1978) with a resolution of 1 nm. There is apparently general agreement, but it is clear that the variation of Fraunhofer absorption is a reason for discrepancy that is associated with the precision in wavelength.

We have adopted as a reference spectrum the SUSIM data. In Fig. 13, the SUSIM solar irradiances between 375 and 400 nm are plotted at each 0.05 nm, along with their averaged values over 1 nm intervals. The variation by more than a factor of 4 in that region of the irradiance is related to the influence of the Fraunhofer spectrum, as clearly

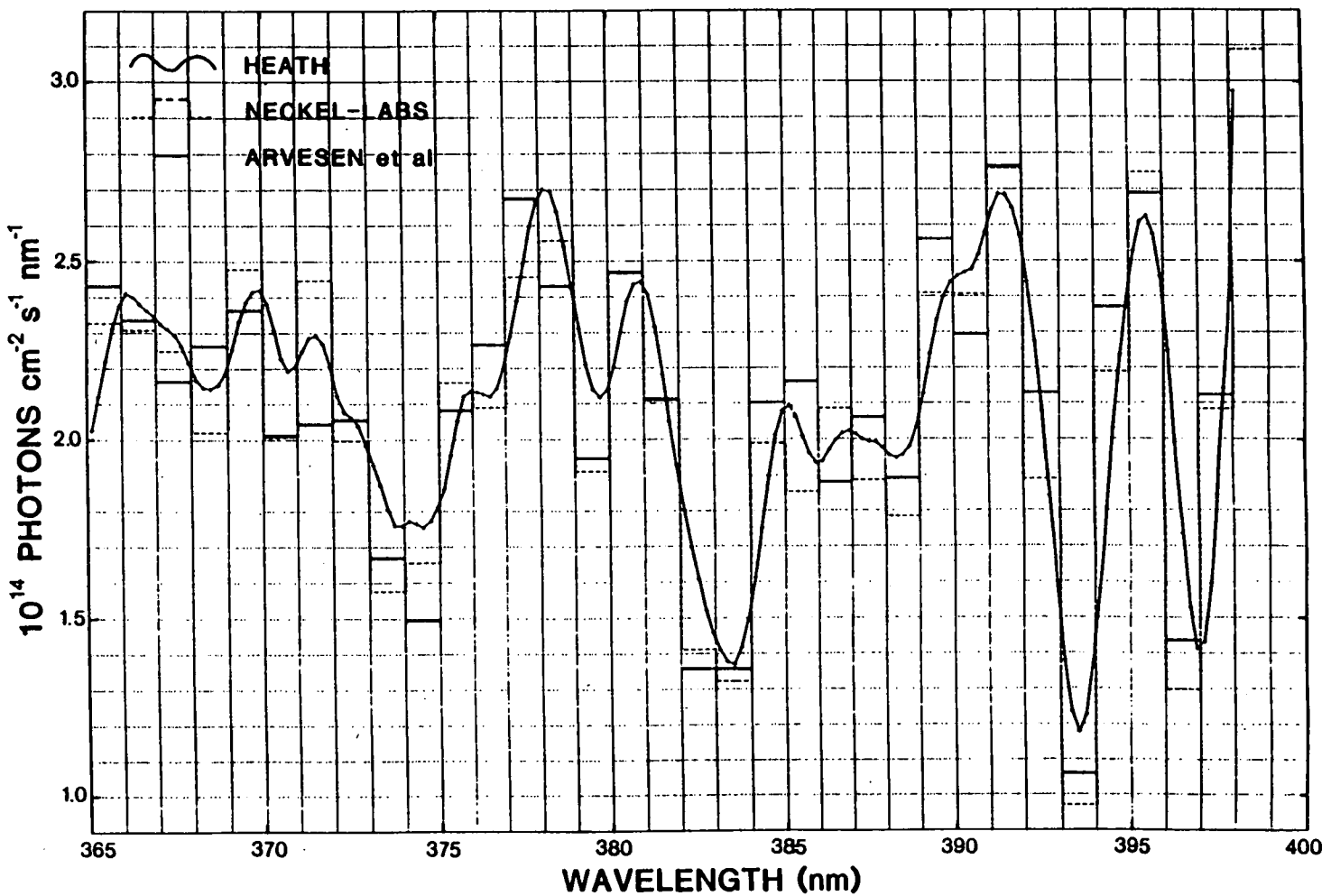

Fig. 11 - Comparison of solar irradiances deduced from observations made by Arvesen et al., Heath, Neckel and Labs. See text.

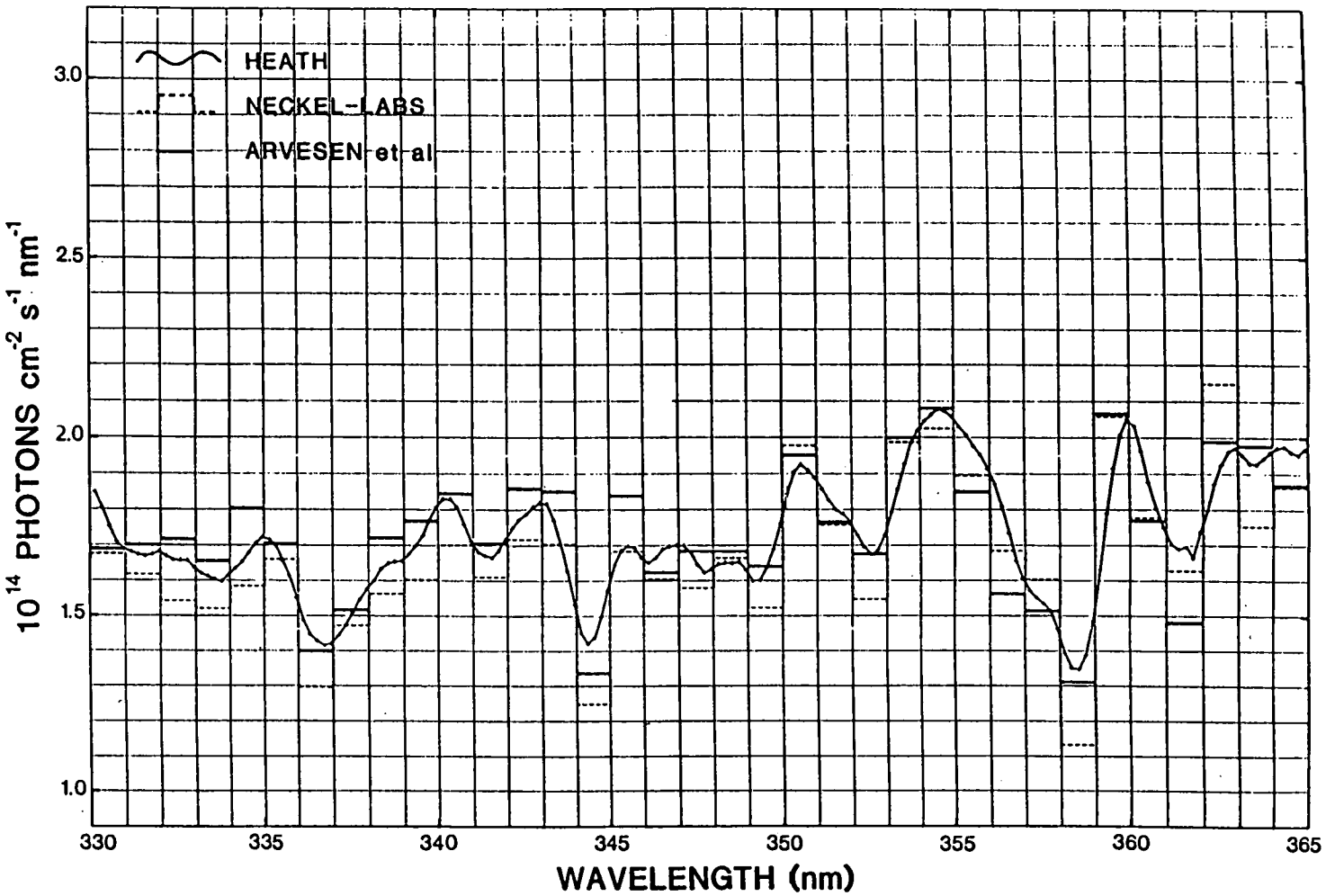

Fig. 12 - As Fig. 11.

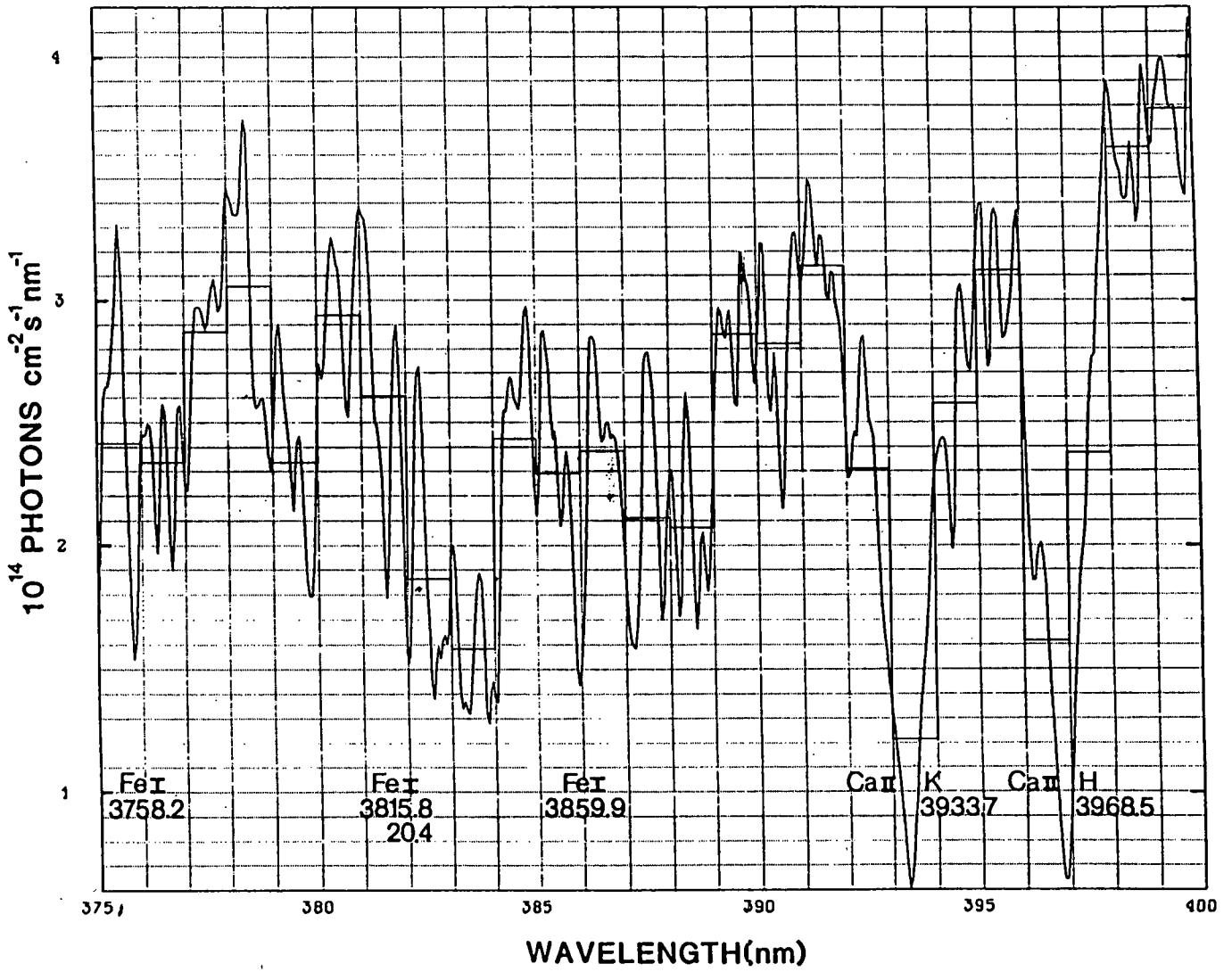

Fig. 13 - Solar spectral irradiances from Spacelab 2 (SUSIM) with detailed structure (0.05 nm) and averaged values in 1 nm intervals between 375 and 400 nm.

indicated by the H and K lines of ionized calcium. The numerical results for 1 nm intervals listed in Table 9 illustrate the fact that at 393-394 nm and at 396-397 nm the ratios SUSIM/HEATH and SUSIM/ARVESEN or SUSIM/NECKEL are not in agreement, bacause of an anomaly in the wavelength comparison. Several examples of inaccuracy in the data averaged over 1 nm intervals are found and cannot be predicted. This emphasizes the importance of having clear and constant systems of analysis; they are necessary to obtain accurate values of solar irradiances for spectral intervals of 1 nm or less. The results of the analysis between 375 and 400 nm are illustrated in Fig.14. All the SUSIM data are systematically higher than the other values. The relative values which are also presented in this figure for 5 nm intervals show that the values deduced from Heath, Arvesen et al., and Neckel and Labs are systematically 15% lower than the SUSIM data.

Fig. 15, Table 10 and Fig. 16 for the 350-375 nm spectral range are similar to Fig. 13, Table 9 and Fig. 14 described above for the 375-400 nm region. The difference between the SUSIM and other data decreases overall from about 15% to 5% from 375 to 350 nm. Agreements and disagreements occur randomly between the various values of the solar irradiances in 1 nm intervals when a precision of better than 10% is required.

In Fig. 17, the SUSIM solar irradiances between 325 and 350 nm are plotted at each 0.05 nm with their averaged values over 1 nm intervals. Fig. 18 and Table 11 compare the SUSIM data for 1 nm and 5 nm intervals with the results deduced from Heath, Arvesen et al., and Neckel and Labs (1984) in the 325-350 nm spectral range. There is excellent agreement between the data deduced from SUSIM and from Arvesen et al. (see Table 11); the results obtained by Neckel and Labs are systematically lower (listed in Table 11), of the order of 7±3% and there is a similar tendency for the values deduced from Heath, reaching about 5%. There are still differences in the ratio SUSIM/HEATH such as 1.14, 0.92 and 1.12 for 343-344 nm, 344-345 nm and 345-346 nm, respectively; such differences are associated with a wavelength problem. In addition, in

TABLE 9.- Solar spectral irradiances averaged in 1 nm intervals, $q_\infty = 10^{14}$ photons cm^{-2} s^{-1}, and in 5 nm intervals, $q_\infty = 10^{15}$ photons cm^{-2} s^{-1}, deduced from Spacelab 2 (SUSIM) and compared with the results deduced from observations of Heath, of Arvesen et al., and of Neckel and Labs between 400 and 375 nm.

Wavelength Interval (nm)	q_∞ SUSIM 1 nm	q_∞ SUSIM 5 nm	Ratio SUSIM HEATH	Ratio HEATH SUSIM	Ratio SUSIM ARVESEN	Ratio ARVESEN SUSIM	Ratio SUSIM NECKEL	Ratio NECKEL SUSIM	Ratio MEAN SUSIM
375-376	2.42		1.20		1.17		1.12		
6 7	2.34		1.10		1.04		1.12		
7 8	2.87	1.35	1.16	0.83	1.08	0.84	1.17	0.83	0.83
8 9	3.06		1.21		1.23		1.19		
379-380	2.34		1.09		1.21		1.22		
380 1	2.94		1.26		1.20		1.19		
1 2	2.61		1.25		1.21		1.24		
2 3	1.86	1.14	1.19	0.81	1.35	0.82	1.32	0.81	0.81
3 4	1.58		1.15		1.16		1.20		
4 5	2.43		1.29		1.18		1.22		
5 6	2.29		1.16		1.05		1.24		
6 7	2.38		1.21		1.27		1.14		
7 8	2.11	1.17	1.08	0.86	1.03	0.91	1.12	0.86	0.87
8 9	2.07		1.06		1.10		1.16		
389-390	2.86		1.24		1.13		1.19		
390 1	2.82		1.14		1.23		1.17		
1 2	3.14		1.22		1.13		1.14		
2 3	2.31	1.21	1.20	0.85	1.06	0.88	1.22	0.88	0.87
3 4	1.22		0.96		1.17		1.25		
4 5	2.57		1.25		1.10		1.17		
5 6	3.12		1.25		1.15		1.13		
6 7	1.62		0.96		1.07		1.24		
7 8	2.37	1.45	1.18	0.87	1.18	0.89	1.13	0.86	0.87
8 9	3.63		1.13		1.09		1.17		
399-400	3.79		1.15		1.12		1.14		

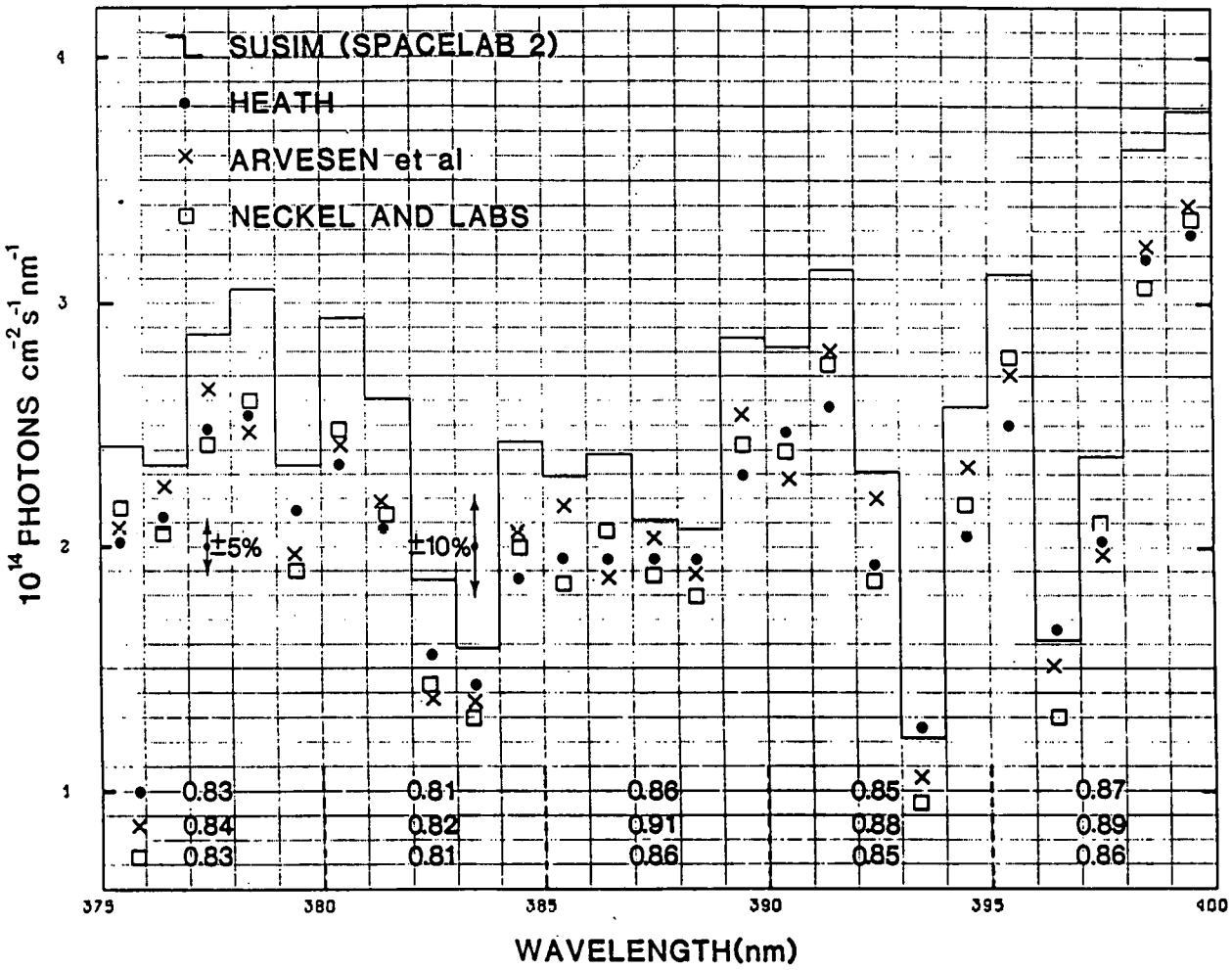

Fig. 14 - Comparison of spectral irradiances for 1 nm intervals between 375 and 400 nm. Ratios for 5 nm intervals are also given : SUSIM to Heath, to Arvesen et al. and to Neckel and Labs, respectively.

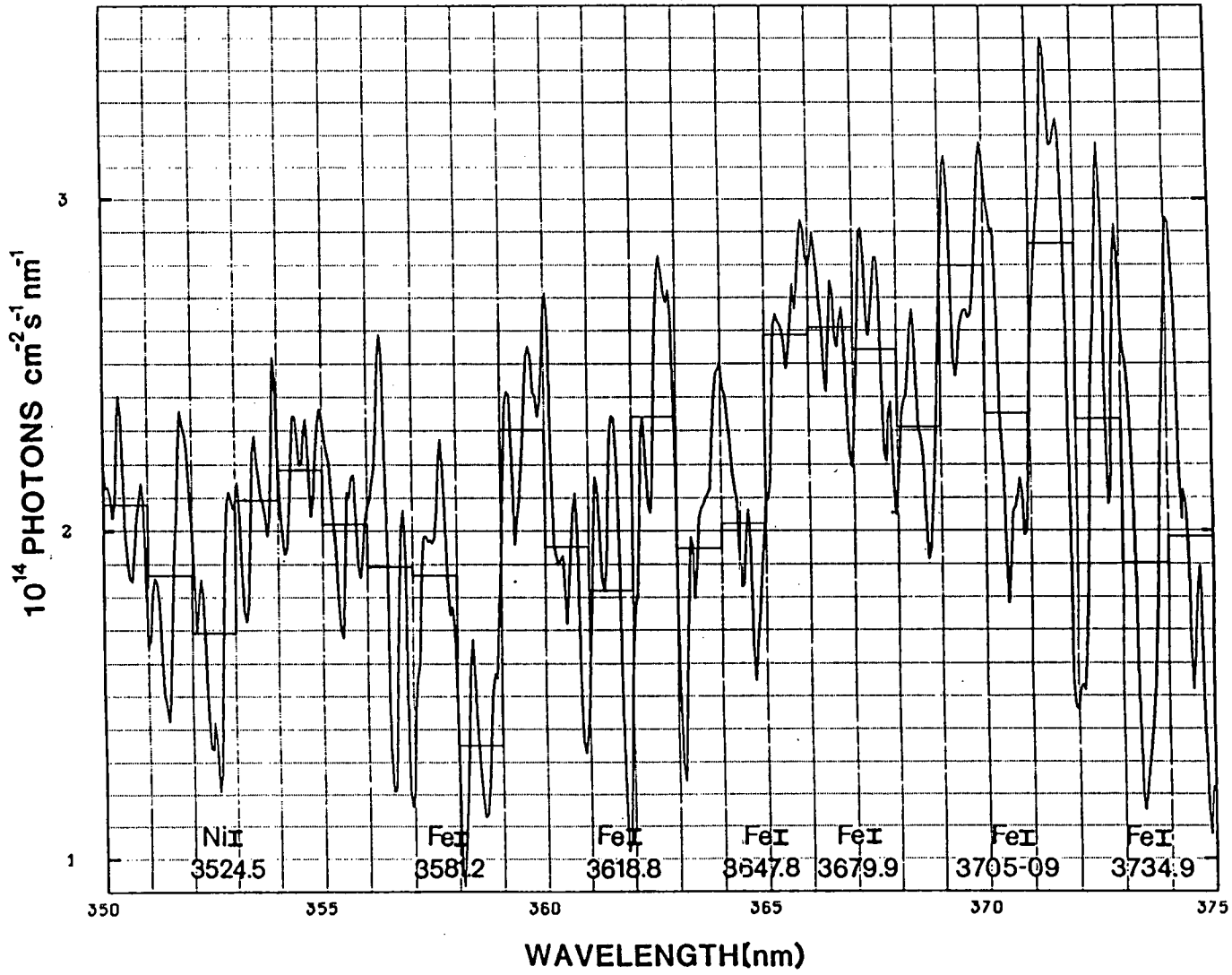

Fig. 15 - As Fig. 13; between 350 and 375 nm.

TABLE 10.- Solar spectral irradiances averaged in 1 nm intervals, $q_\infty = 10^{14}$ cm^{-2} s^{-1}, and in 5 nm intervals, $q_\infty = 10^{15}$ photons cm^{-2} s^{-1}, deduced from Spacelab 2 measurements and compared with results deduced from observations of Heath, Arvesen et al. and of Neckel and Labs between 375 and 350 nm.

Wavelength Interval (nm)	q_∞ SUSIM 1 nm	q_∞ SUSIM 5 nm	Ratio SUSIM HEATH	Ratio HEATH SUSIM	Ratio SUSIM ARVESEN	Ratio ARVESEN SUSIM	Ratio SUSIM NECKEL	Ratio NECKEL SUSIM	Ratio MEAN SUSIM
350-351	2.08		1.12		1.06		1.05		
1 2	1.87		1.06		1.06		1.06		
2 3	1.69	0.99	1.01	0.93	1.01	0.95	1.09	0.94	0.94
3 4	2.09		1.10		1.05		1.05		
4 5	2.18		1.07		1.05		1.07		
5 6	2.02		1.05		1.09		1.06		
6 7	1.89		1.12		1.20		1.12		
7 8	1.87	0.94	1.27	0.89	1.21	0.88	1.16	0.94	0.90
8 9	1.35		0.97		1.07		1.19		
359-360	2.30		1.24		1.11		1.12		
360 1	1.95		1.07		1.10		1.10		
1 2	1.82		1.08		1.23		1.12		
2 3	2.34	1.01	1.24	0.92	1.18	0.91	1.09	0.91	0.91
3 4	1.95		1.02		0.99		1.11		
4 5	2.02		1.04		1.09		1.09		
5 6	2.59		1.17		1.07		1.11		
6 7	2.61		1.12		1.12		1.13		
7 8	2.54	1.30	1.14	0.86	1.16	0.89	1.13	0.87	0.87
8 9	2.31		1.08		1.03		1.14		
369-370	2.80		1.20		1.18		1.13		
370 1	2.35		1.06		1.17		1.17		
1 2	2.87		1.29		1.38		1.17		
2 3	2.33	1.14	1.15	0.87	1.13	0.81	1.26	0.85	0.84
3 4	1.90		1.07		1.15		1.20		
374-375	1.98		1.13		1.32		1.19		

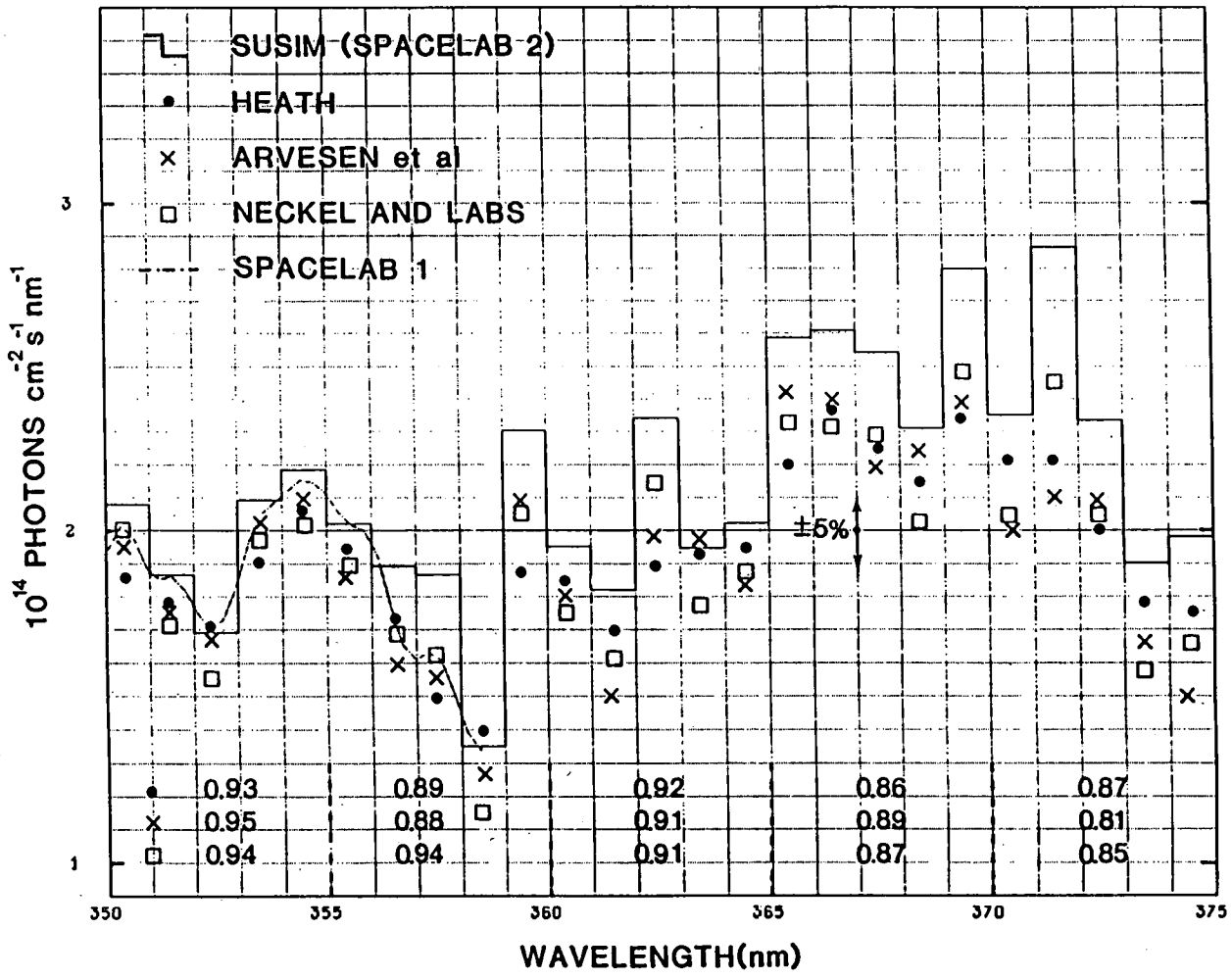

Fig. 16 - As Fig. 14; between 350 and 375 nm.

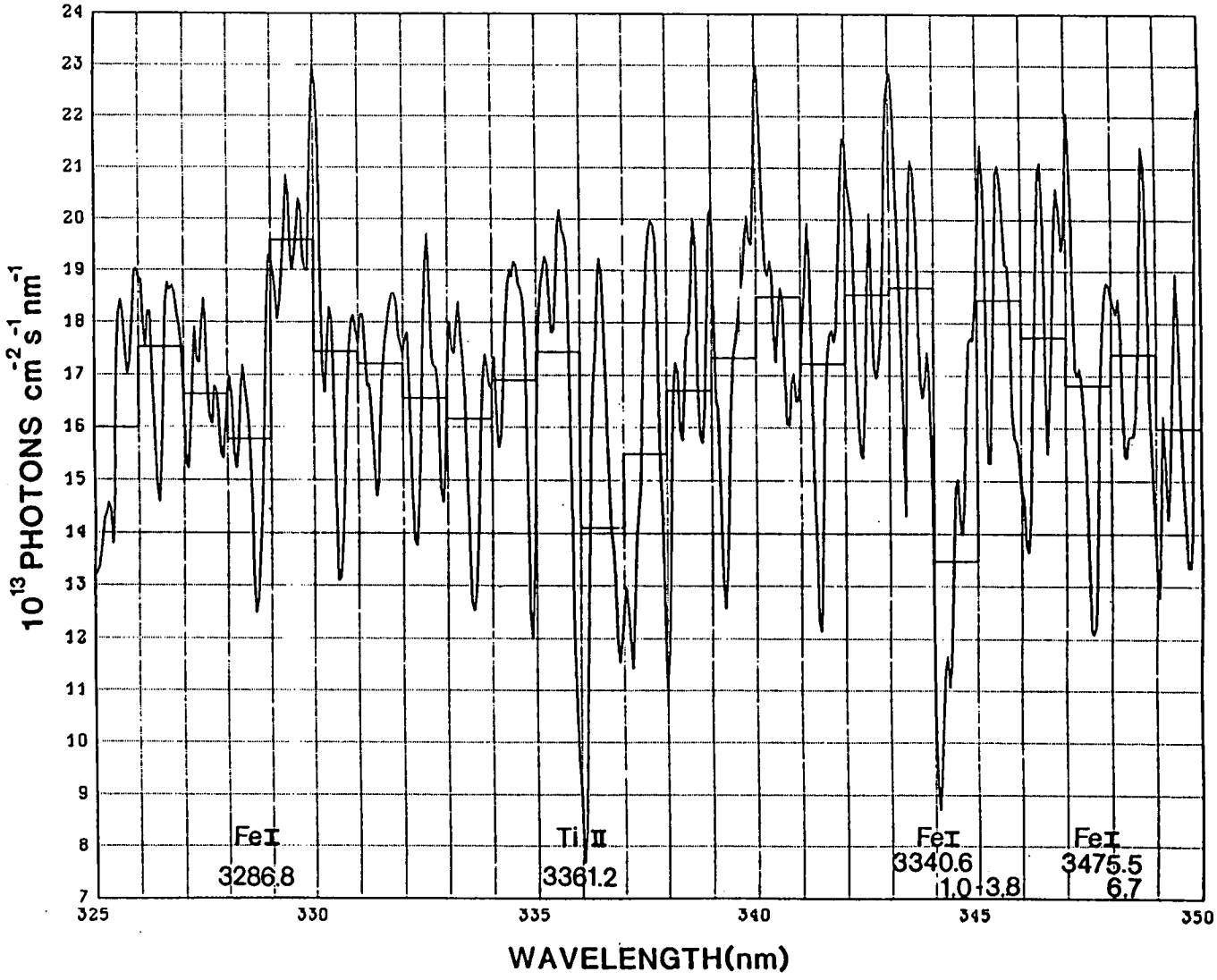

Fig. 17 - As Fig. 13 and 15; between 325 and 350 nm.

TABLE 11.- Solar irradiances averaged in 1 nm and 5 nm intervals, q_∞ = 10^{14} photons cm^{-2} s^{-1}, deduced from Spacelab 2 measurements and compared with results deduced from obsevations of Heath, Arvesen et al. and of Neckel and Labs between 350 and 325 nm.

Wavelength Interval (nm)	q_∞ SUSIM 1 nm	q_∞ SUSIM 5 nm	Ratio SUSIM HEATH	Ratio HEATH SUSIM	Ratio SUSIM ARVESEN	Ratio ARVESEN SUSIM	Ratio SUSIM NECKEL	Ratio NECKEL SUSIM
325-326	1.60		1.07		1.08			
6 7	1.75		1.07		0.93			
7 8	1.66	8.53	1.04	0.95	1.02	1.00		
8 9	1.58		1.00		0.99			
329-330	1.96		1.09		1.02			
330 1	1.74		1.00		1.02		1.04	
1 2	1.72		1.04		1.02		1.06	
2 3	1.65	8.42	1.01	0.98	0.96	1.02	1.07	0.94
3 4	1.62		1.02		0.98		1.07	
4 5	1.69		1.02		0.94		1.06	
5 6	1.74		1.08		1.00		1.05	
6 7	1.41		1.00		1.01		1.08	
7 8	1.55	8.14	1.04	0.96	1.03	1.00	1.05	0.93
8 9	1.67		1.04		0.98		1.07	
339-340	1.77		1.03		1.00		1.11	
340 1	1.85		1.06		1.00		1.09	
1 2	1.72		1.04		1.01		1.07	
2 3	1.85	8.64	1.05	0.96	1.00	1.00	1.07	0.92
3 4	1.87		1.14		1.00		1.09	
4 5	1.35		0.92		1.02		1.08	
5 6	1.84		1.12		1.00		1.03	
6 7	1.77		1.07		1.11		1.10	
7 8	1.68	8.63	1.03	0.95	0.99	0.98	1.06	0.93
8 9	1.74		1.07		1.04		1.05	
349-350	1.60		0.98		0.98		1.05	

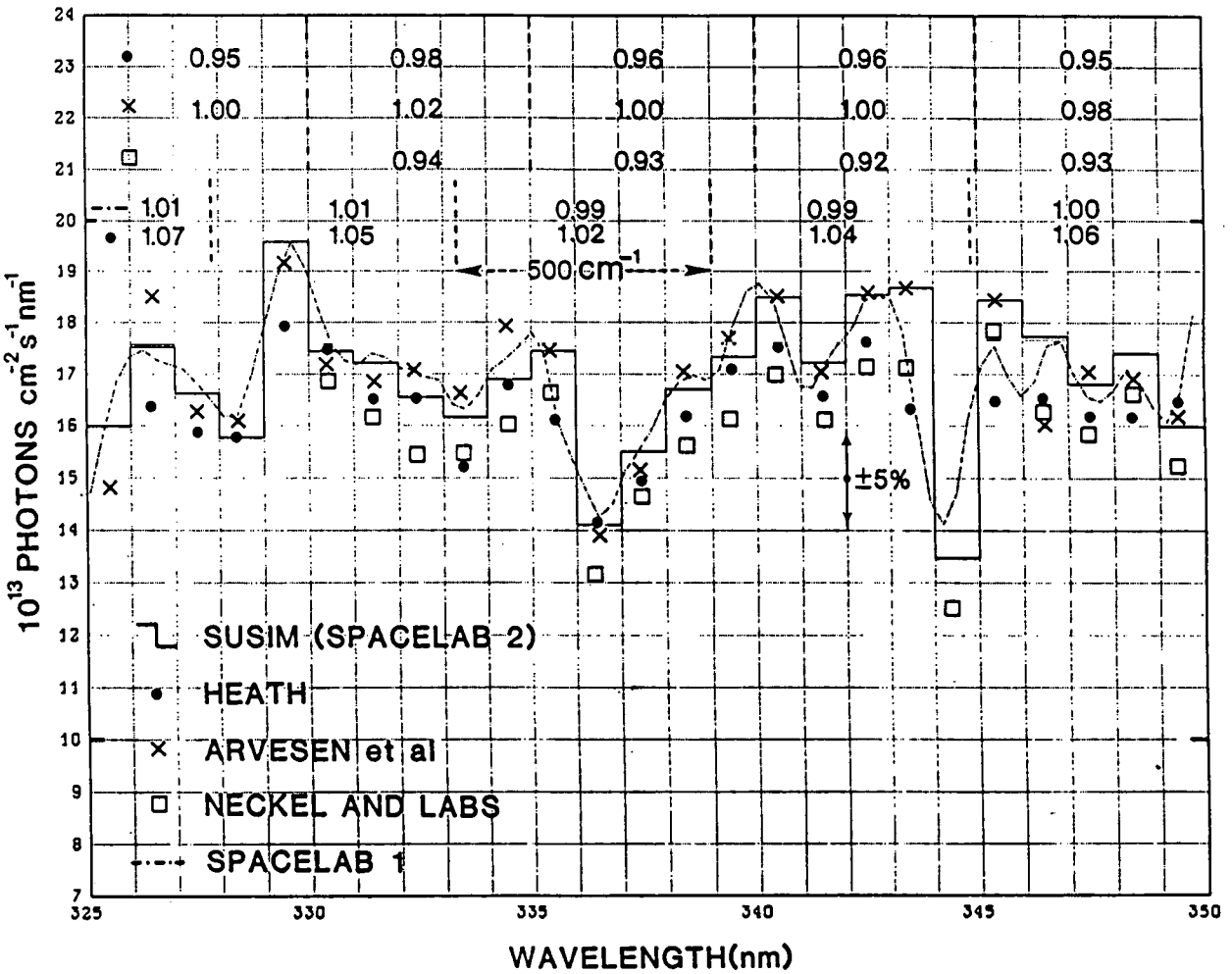

Fig. 18 - As Fig. 14 and 16; between 325 and 350 nm.

this spectral region, it has been possible to make comparison with the data deduced from Spacelab 1 (Labs et al., 1989). Fig. 18 also illustrates the variations of SUSIM data with that of Spacelab 1 for 1 nm intervals (3 observations for 1 nm). A ratio for 500 cm^{-1} interval has been determined and yields the following values : SUSIM-SPACELAB 2/ SPACELAB 1 = 1 and SUSIM/HEATH = 1.04 $\pm$ 0.02. Fig. 18 shows, therefore, that the systematic difference between SUSIM and other data has disappeared; the ratio for ARVESEN/SUSIM is of the order of 1 and HEATH/SUSIM of the order of 0.96.

In the 300-325 nm spectral range (Fig. 19) the solar spectrum has a structure complicated by the absorption lines; it corresponds to variations of a factor of 5 in the detailed irradiances. The numerical values listed in Table 12 for 1 nm indicate the disparity of the observational results; the precision is of the order of + 15%. Nevertheless, when a comparison is made between the irradiances of Spacelab 1 and Spacelab 2 - SUSIM for 500 cm^{-1} intervals as illustrated in Fig. 20, agreement is reached to within $\pm$ 5%. But the values deduced from the measurements made by Heath indicate that they are 9 $\pm$ 1% lower than the SUSIM data. Thus, the SUSIM irradiances should be recommended as the reference data. Nevertheless, the systematic difference of about 10% in an important photolytic region, namely 300-325 nm, requires special analysis.

4. *SOLAR SPECTRAL IRRADIANCES IN THE OZONE ABSORPTION REGION : BETWEEN 300 and 200 NM*

A first general comparison between the various observational results between 300 and 200 nm has been made for 500 cm^{-1} intervals. The SUSIM (Spacelab 2, VanHoosier et al, 1987) data have been adopted to determine a reference spectrum over 500 cm^{-1} intervals. These observations were made between July 29 and August 6, 1985, and correspond to a low level of solar activity; the solar radio fluxes have fallen to relatively low values : 257 $\pm$ 2 at 3 cm, 86 $\pm$ 2 at 8 cm and 80 $\pm$ 2 at 10 cm; the smallest values for a minimum of solar activity are about 250,

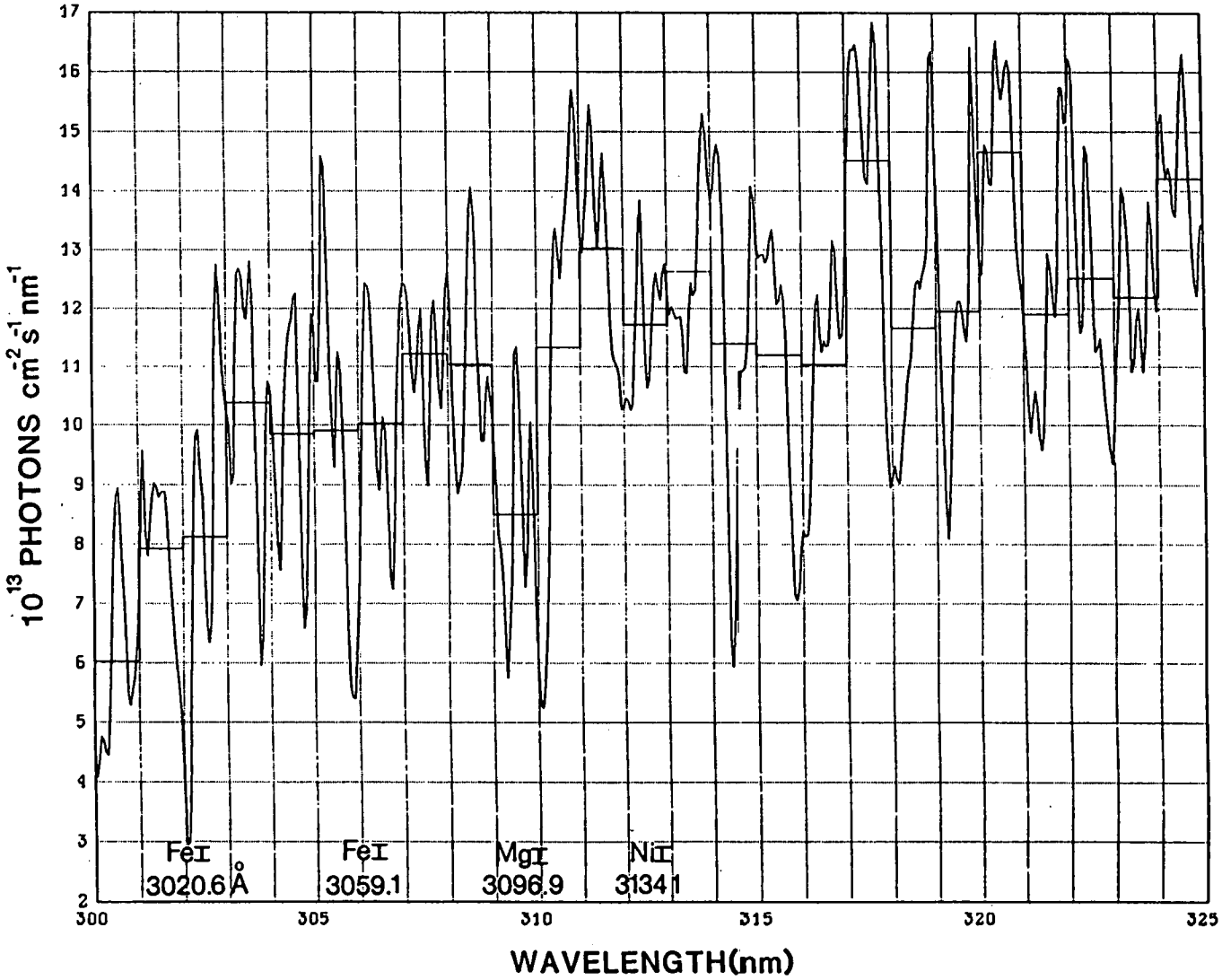

Fig. 19 - As Fig. 13-17; between 300 and 325 nm.

TABLE 12.- Solar irradiances averaged in 1 nm and 5 nm, intervals, $q_\infty = 10^{14}$ photons cm^{-2} s^{-1}, deduced from Spacelab 2 measurements and compared with results deduced from observations of Heath, Arvesen et al., of Mentall et al., and of Mentall and Williams (II)

Wavelength Interval (nm)	q_∞ SUSIM 1 nm	q_∞ SUSIM 5 nm	Ratio SUSIM HEATH	Ratio HEATH SUSIM	Ratio SUSIM ARVESEN	Ratio ARVESEN SUSIM	Ratio SUSIM MENTALL I	Ratio SUSIM MENTALL II
300-301	0.603		0.92		0.73		1.01	0.85
1 2	0.793	4.23	1.14	0.96	0.86	1.02	1.06	0.92
2 3	0.812		1.06		1.00		1.16	1.09
3 4	1.04		1.06		1.19		1.04	0.88
4 5	0.985		1.04		1.15		1.11	0.93
5 6	0.990		1.07		1.04		1.02	0.86
6 7	1.00	5.06	1.11	0.91	1.04	0.90	1.09	1.05
7 8	1.12		1.12		1.07		1.05	1.00
8 9	1.10		1.13		1.23		1.03	0.94
309-310	0.851		1.03		1.06		1.03	0.92
310 1	1.13		1.10		1.07		1.15	1.15
1 2	1.30	6.00	1.13	0.91	1.15	0.93	1.02	0.91
2 3	1.17		1.09		1.04		1.13	1.02
3 4	1.26		1.11		1.10		1.13	0.97
4 5	1.14		1.05		1.00		1.06	0.93
5 6	1.12		1.11		1.04		1.07	0.88
6 7	1.10	6.02	1.04	0.93	0.96	0.98	1.19	1.09
7 8	1.45		1.19		1.13		1.11	0.97
8 9	1.16		1.05		0.98		1.21	1.04
9-320	1.19		1.01		0.98		1.08	0.94
320 1	1.47		1.15		1.06		1.09	0.95
1 2	1.19	6.55	1.03	0.92	0.98	0.90	1.09	0.99
2 3	1.25		1.02		1.08		1.01	0.91
3 4	1.22		1.09		1.20		1.15	1.05
324-325	1.42		1.11		1.30		1.09	0.99

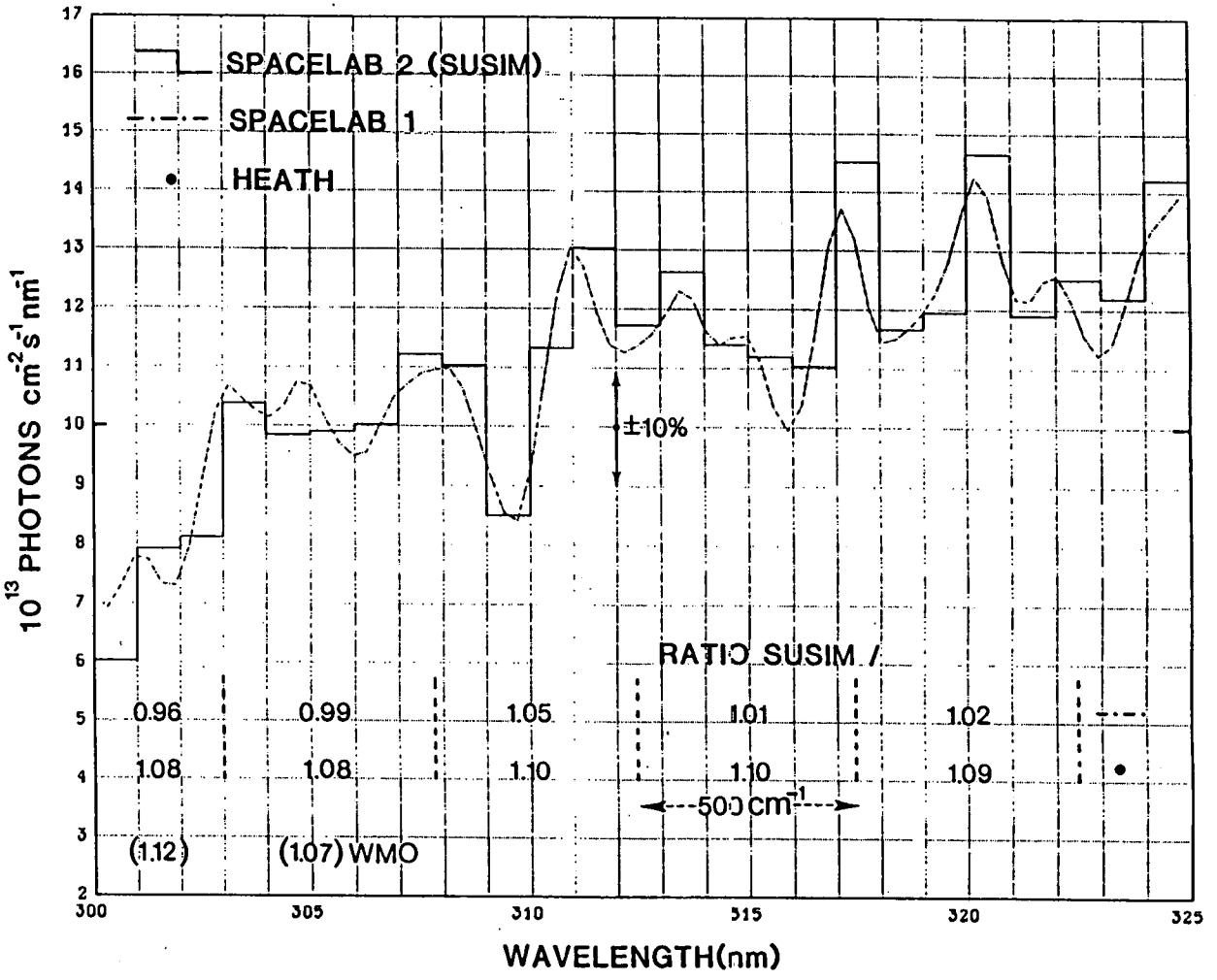

Fig. 20 - As Fig. 14-18; between 300 and 325 nm.

70 and 65, respectively. The SUSIM results are illustrated in Fig. 21 and are compared with other observational results or compilations. The values published in WMO (1985) are based on measurements made between 1978 and 1984: for example, by Mentall et al (1981) on 15 September, 1980 when the solar radiofluxes were 311, 148 and 154 at 3, 8 and 10 cm, respectively, by Heath (1980) on 7 November 1978 with 306, 159 and 175 solar radiofluxes at 3, 8 and 10 cm, respectively; and by Mount and Rottman (1985) on 25 July 1983 with the corresponding solar fluxes of 300, 135 and 137 at 3, 8 and 10 cm, respectively. This WMO reference system is represented in Fig. 2.1. The results of the compilation by Brasseur and Simon (1981) are also depicted in that figure. From direct addition of the solar irradiances at various wavelengths published by Labs et al (1987), it is possible to utilize their data obtained in Spacelab 1 on 5 and 6 December 1983 when the solar radiofluxes were 270, 94 and 95 at 3, 8 and 10 cm, respectively.

The extrapolated balloon data of Anderson and Hall (1983) have been added to these determinations in Fig. 22; it shows the distribution of the ratios to the reference data (SUSIM) of the various irradiances in 500 cm^{-1} intervals between 42000 and 32000 cm^{-1}. This figure illustrates the distribution of the various values. Between 48000 and 28000 cm^{-1} (λ_{air} = 208.3-357.1 nm) over 40 intervals of 500 cm^{-1} there is an almost perfect agreement between the results of Spacelab 2 and Spacelab 1. The mean ratio is 1.00, with 55% of the values agreeing within $\pm$ 1%, and 70%, 85% and 95% within $\pm$ 2%, $\pm$ 3% and $\pm$ 4%, respectively; two anomalous values correspond to - 5% and + 8%. There is a systematic difference between the SUSIM reference data and the WMO irradiance values for 32 intervals between 47500 cm^{-1} and 32000 cm^{-1} (λ_{air} 208.3-312.5 nm) : 1.04 $\pm$ 0.03 for 50% of the values and 1.04 $\pm$ 0.08 for all values. For the compilation of Brasseur and Simon, 31 intervals between 48000 cm^{-1} and 32500 cm^{-1} (λ_{air} 208.3-325.0 nm), the mean ratio is 1.00 $\pm$ 5% for 60% of the values and 1.00 $\pm$ 10% to include 95%. The Mentall et al results lead to a ratio 1.09 $\pm$ 0.05, i.e. to about - 10% $\pm$ 5% of the SUSIM reference spectrum. If comparison is made between the Mentall et al and Heath data for 40 intervals of 500 cm^{-1}, the following ratios are obtained :

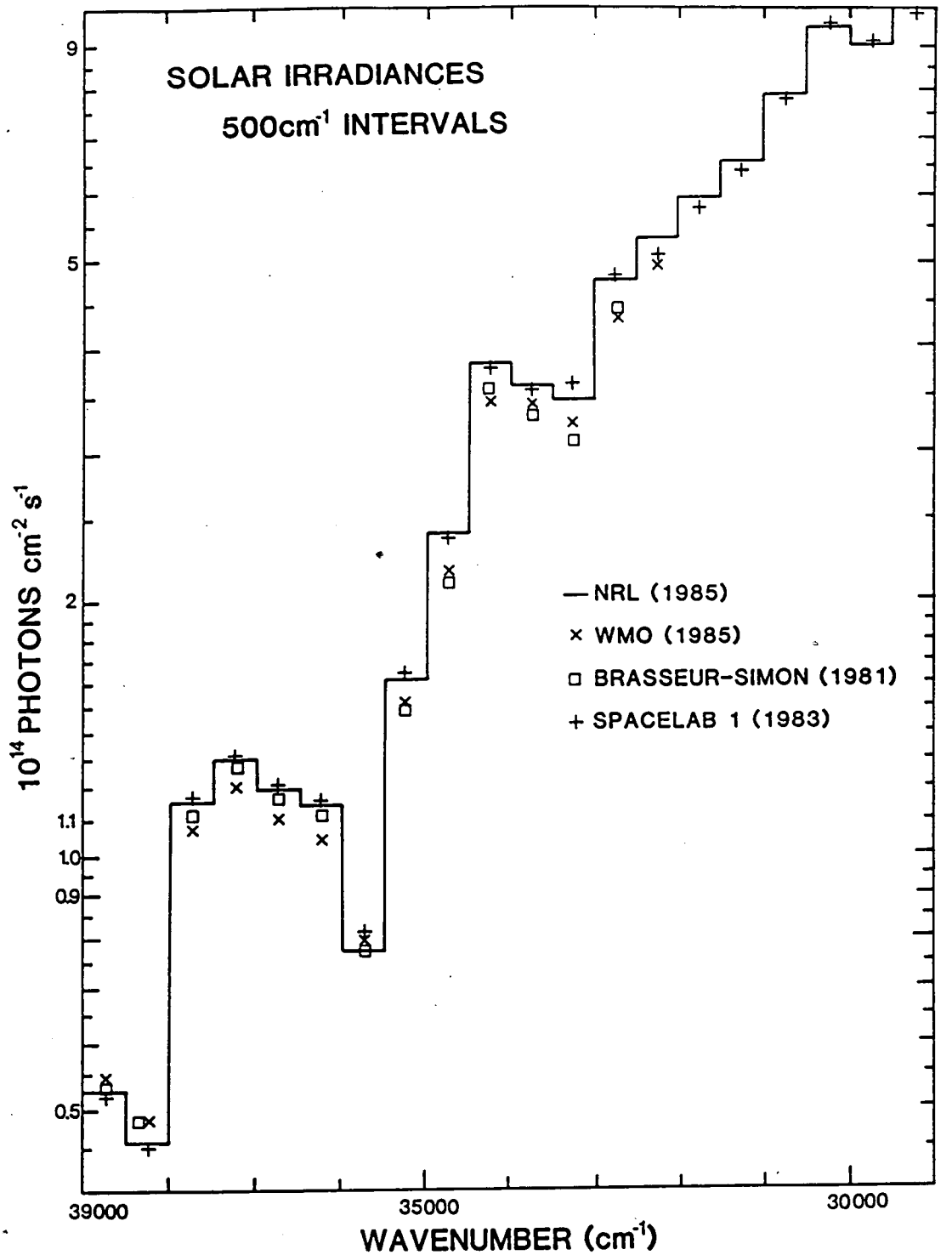

Fig. 21 - Spectral solar irradiances between 39000 and 29000 cm^{-1}. 500 cm^{-1} intervals.

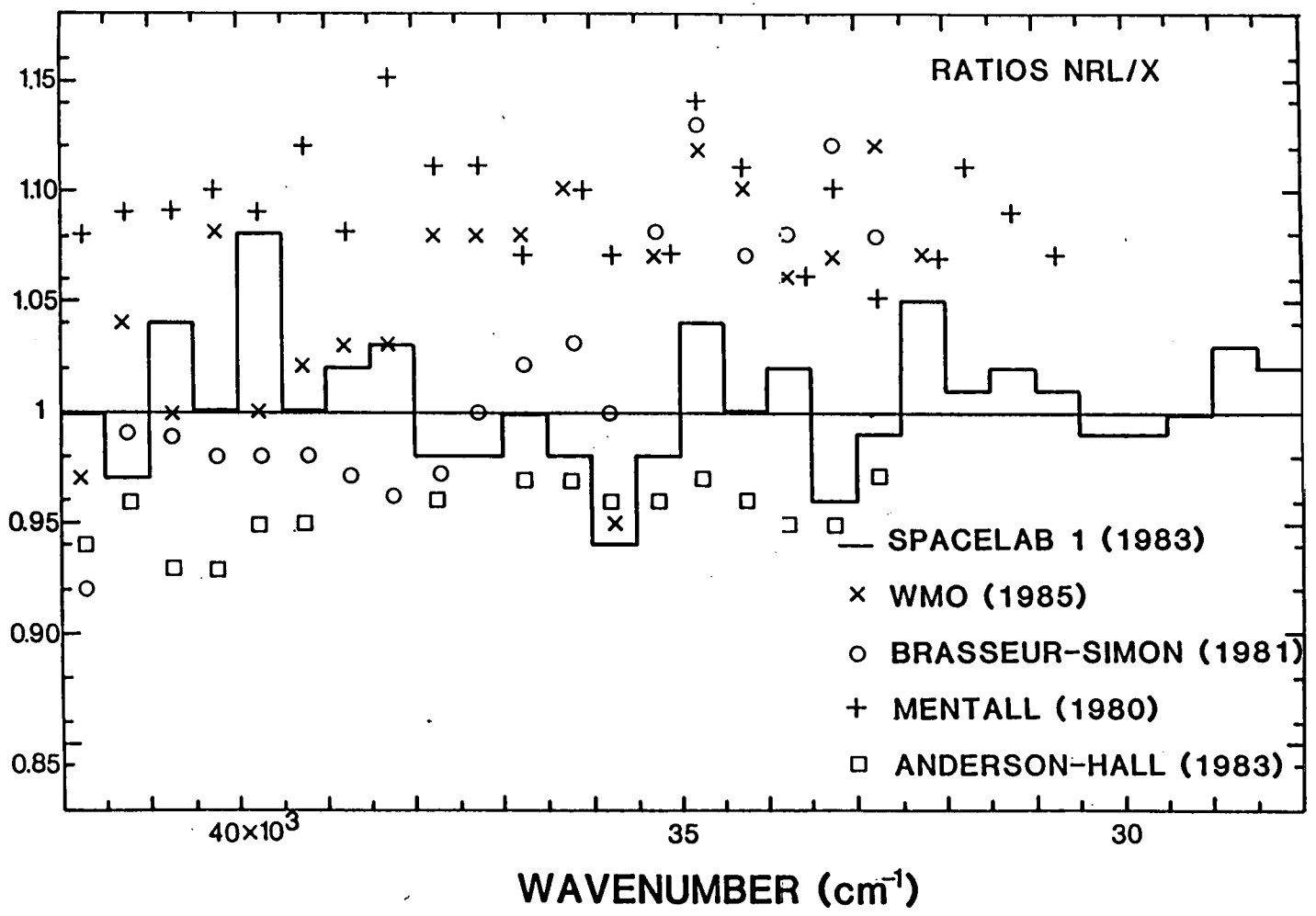

Fig. 22 - Comparison of ratios of spectral solar irradiances between 42000 and 28000 cm^{-1}. The 500 cm^{-1} intervals deduced from SUSIM OBSERVATIONS are adopted as the reference spectrum.

1.00 ± 1% for at least 50%, ± 2% for 65%, ± 3% for 80% and ± 7% for 100 % of all values.

Finally, Fig. 22 shows that the Anderson-Hall data are systematically higher than the SUSIM data, since the ratio NRL/Anderson-Hall is less than 1. The mean value is 0.94 ± 2% for about 50% of the values and falls within 0.94 ± 4% for more than 90% of the data. Thus, the general accuracy of the irradiance data in this part of the ultraviolet spectrum would be of the order of ± 10% with random errors of ± 10% for 500 cm^{-1} intervals.

An analysis has also been made for 1 nm intervals based on the SUSIM results as a reference spectrum. Figures 23, 25, 27 and 29 illustrate the SUSIM irradiances with their 1 nm averaged values between 300 and 200 nm. The 1 nm irradiances deduced from SUSIM are compared in Fig. 24, 26, 28 and 30 with the irradiances (3 values for 1 nm) obtained by Labs et al. on Spacelab 1. The corresponding values for the ratio SUSIM/WMO and SUSIM-Spacelab 2/LABS-Spacelab 1 are also reproduced in these figures. The numerical results of a detailed analysis are presented in Fig. 31. The spectral ranges are indicated for each type of observation. The first ratio SUSIM/HEATH is R = 1.10 ± 15% with a deviation of not less than ± 10% for 80% of the 108 ratios. The comparison with Mentall et al for the same spetral range leads to R = 1.10 ± 10% for 98% of all ratios. For the compilation of Brasseur and Simon R = 1.00 ± 15%; a deviation within about 10% is attained by 85% of all ratios. Between 217 and 307 nm, R = 0.95 ± 10% for the extrapolated stratospheric measurementss of Anderson and Hall. Two other groups of irradiances not considered before that were obtained from rocket measurements (Mentall and Williams, 1986) and from the Solar Mesosphere Explorer (Rottman, 1982 and unpublished) have been introduced. The results of a comparison with the SUSIM irradiances provide the following ratios :

SUSIM/MENTALL, R = 0.95 ± 15% and ± 10% for 80% of the spectral range 217-317 nm;

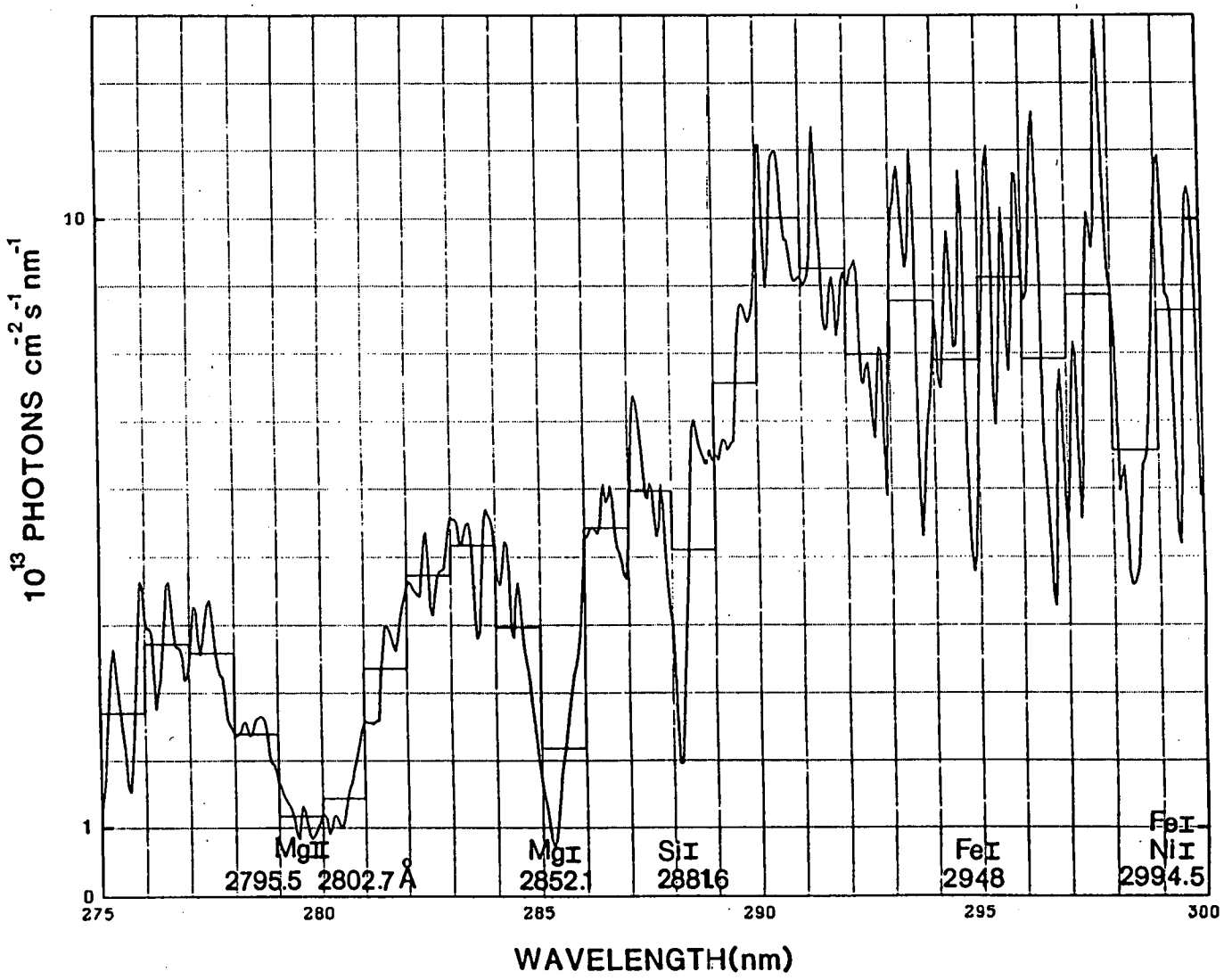

Fig. 23 - Solar spectral irradiances from Spacelab 2 (SUSIM) with detailed structure (0.05 nm) and averaged values in 1 nm intervals. Between 275 and 300 nm.

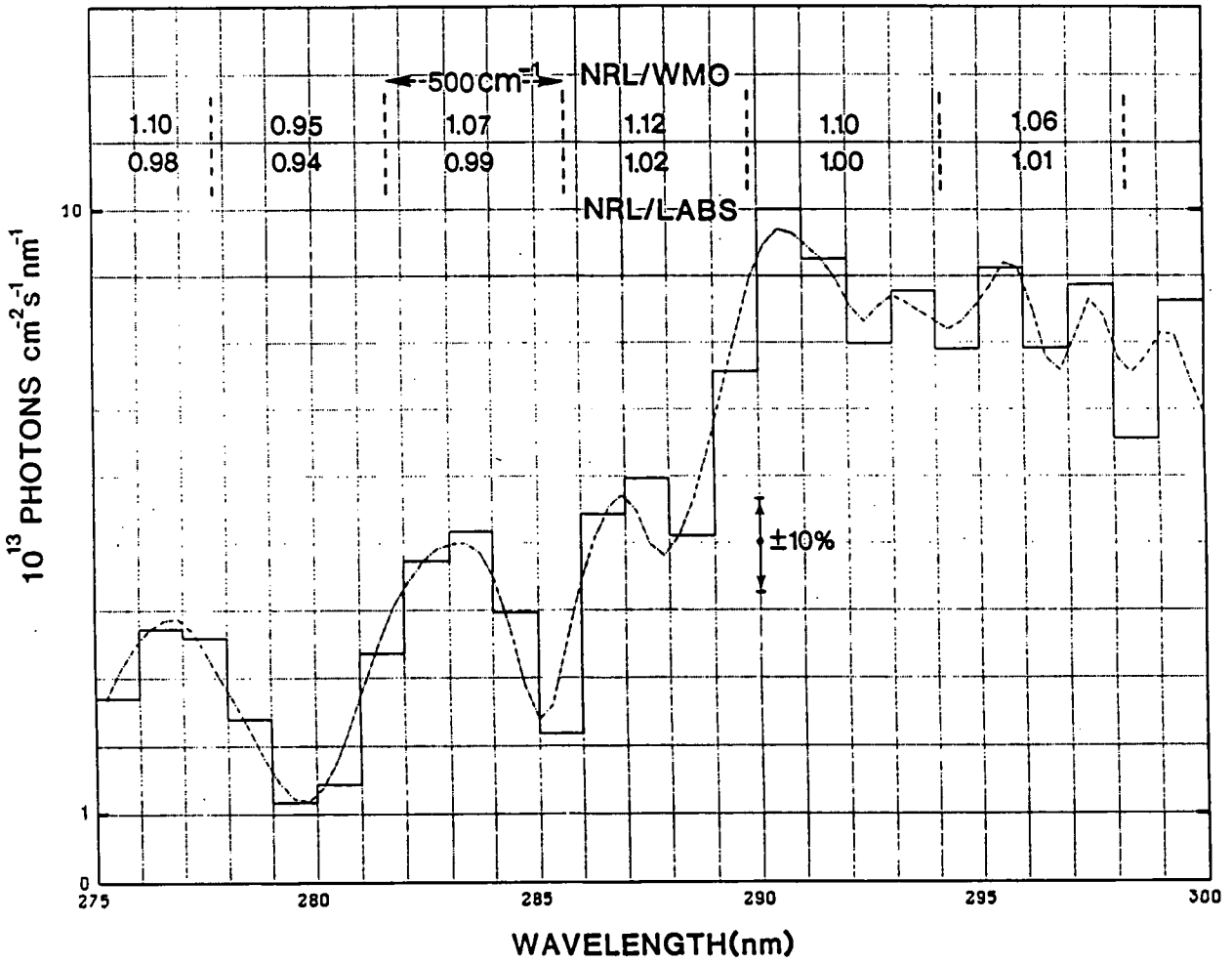

Fig. 24 - Spectral irradiances from Spacelab 2 - SUSIM (1 nm intervals) and from Spacelab 1 (3 values in 1 nm), and comparison of ratios for 500 cm^{-1} : SUSIM/WMO and SUSIM/Spacelab 1. Between 275 and 300 nm.

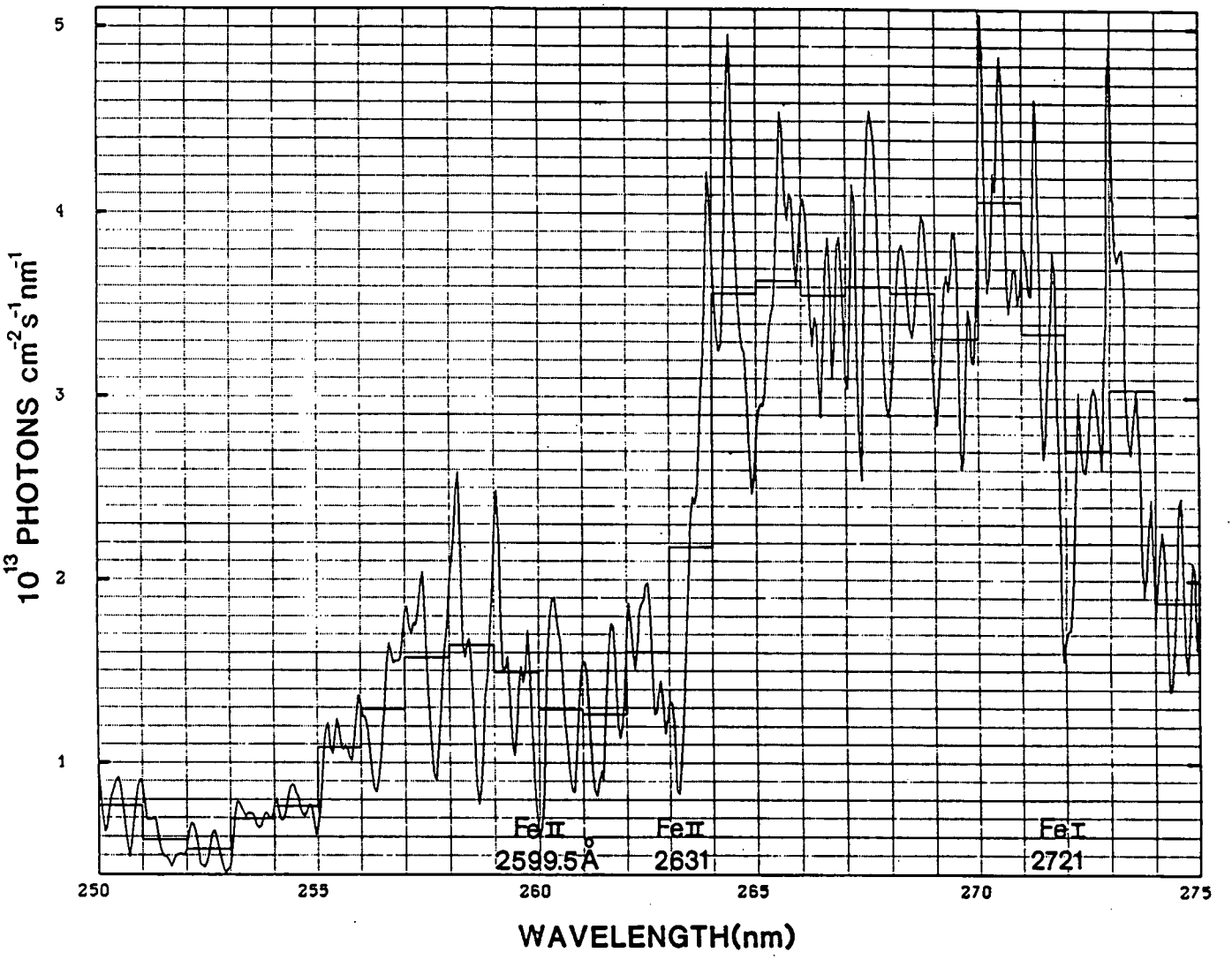

Fig. 25 - As Fig. 23; between 250 and 275 nm.

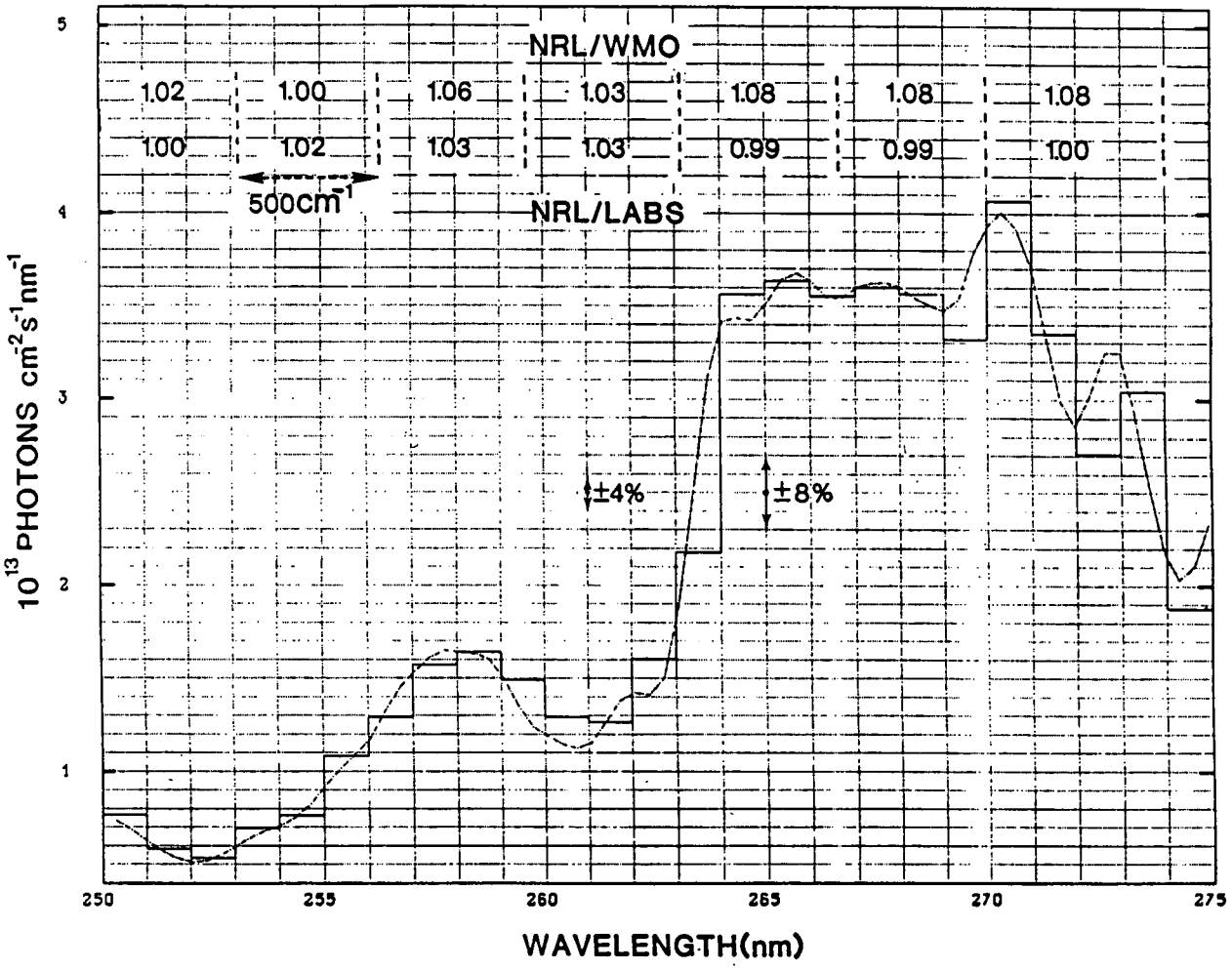

Fig. 26 - As Fig. 24; between 250 and 275 nm.

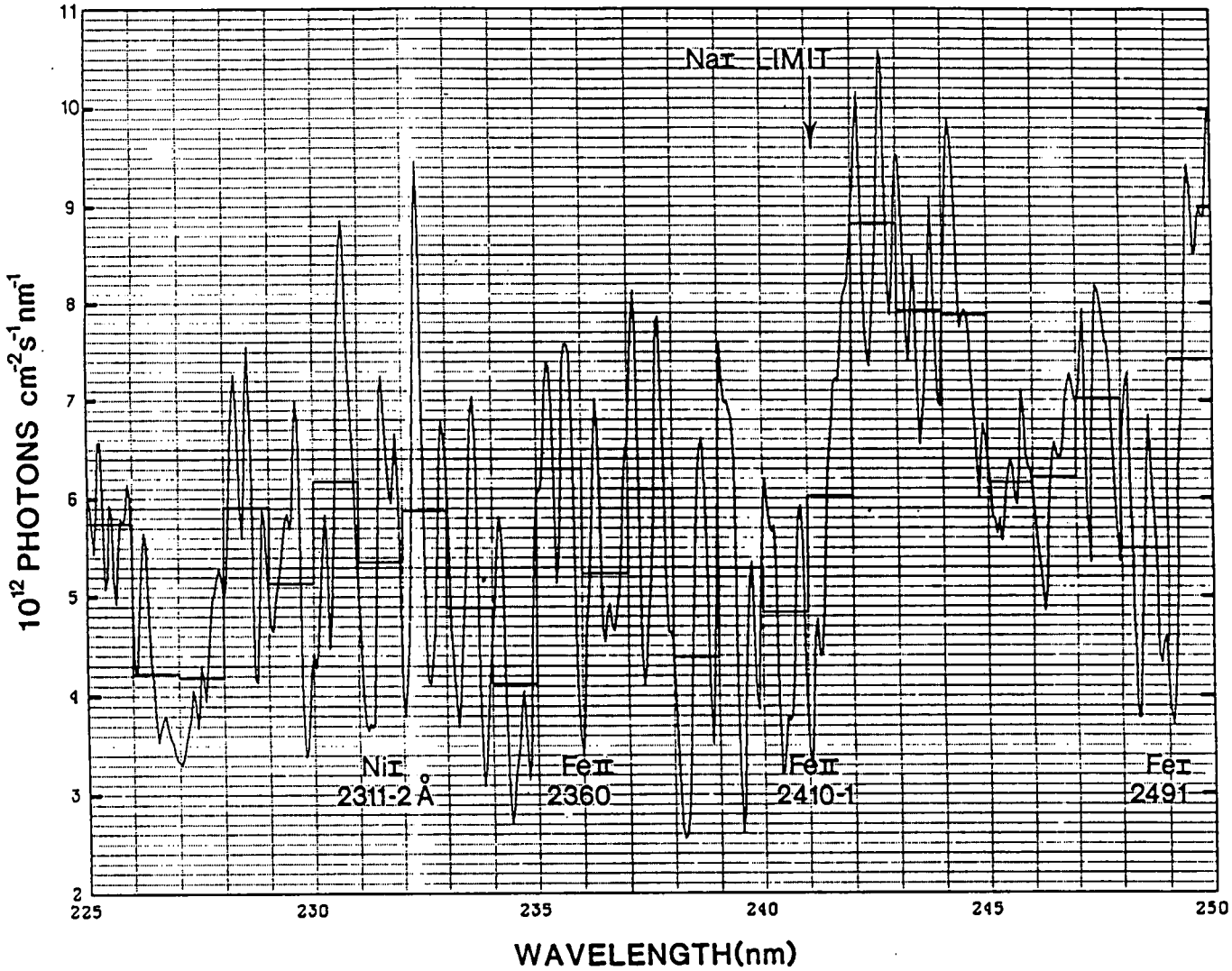

Fig. 27 - As Fig. 23 and 25; between 225 and 250 nm.

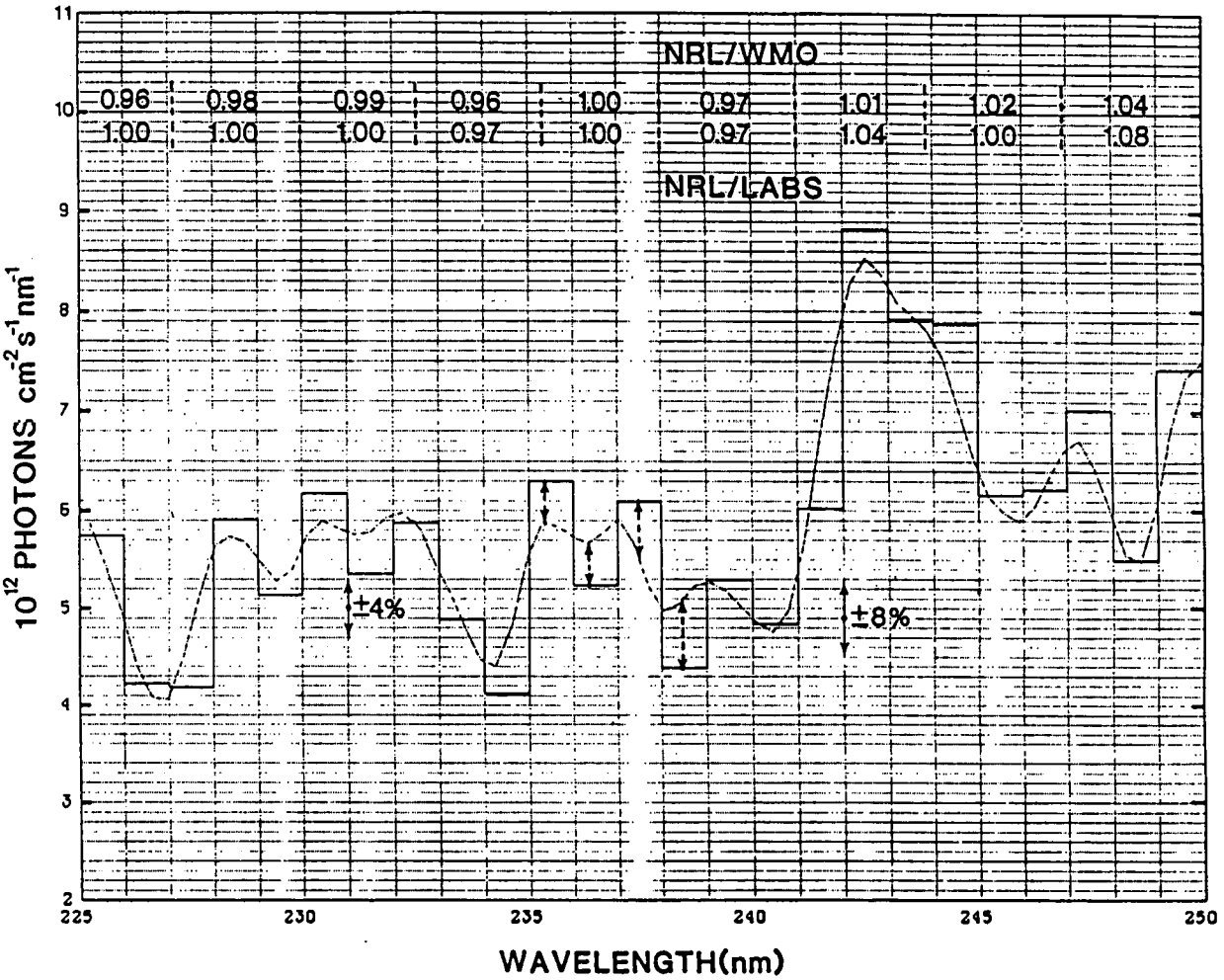

Fig. 28 - As Fig. 24 and 26; between 225 and 250 nm.

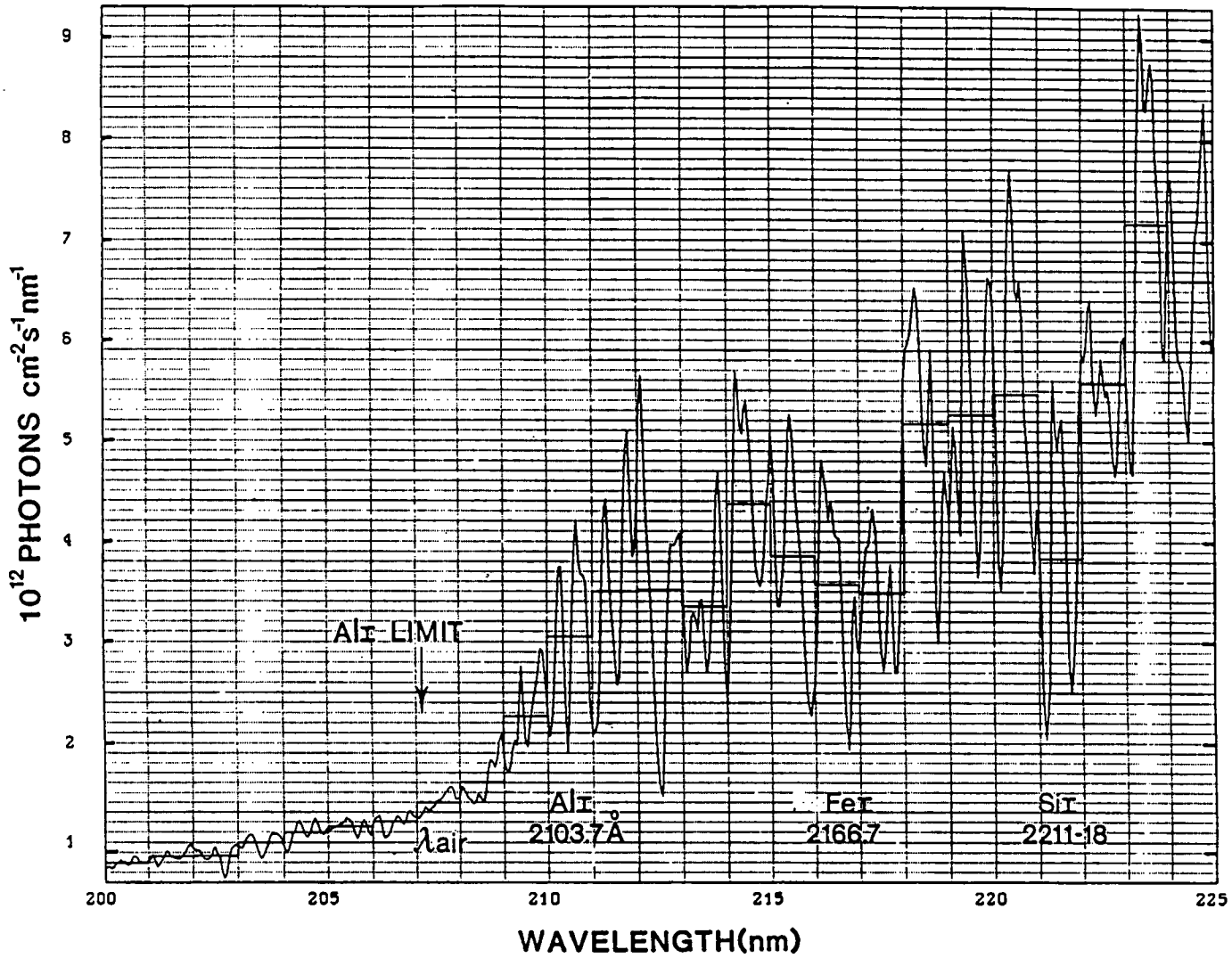

Fig. 29 - As Fig. 23-27; between 200 and 225 nm.

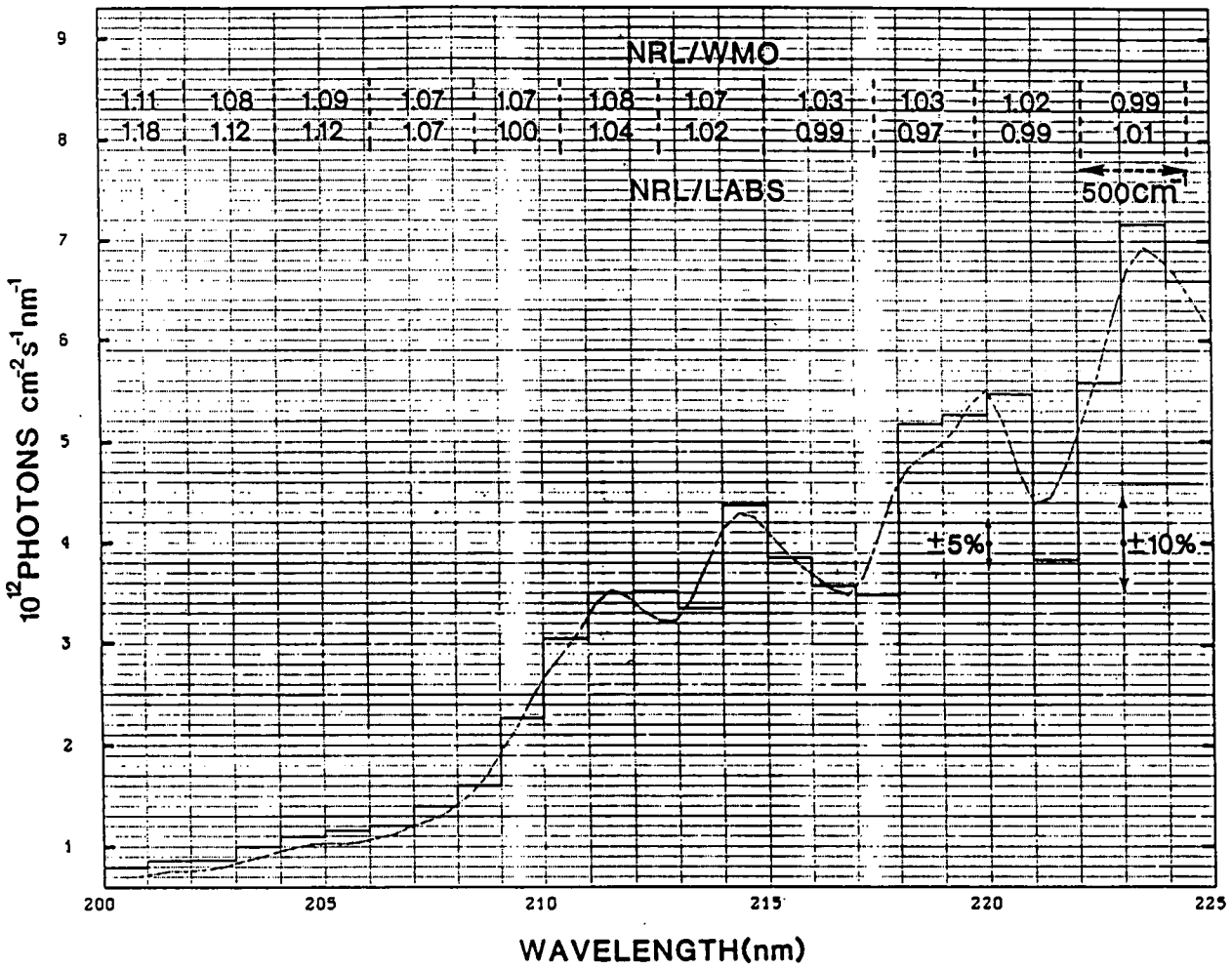

Fig. 30 - As Fig. 24-28; between 200 and 225 nm.

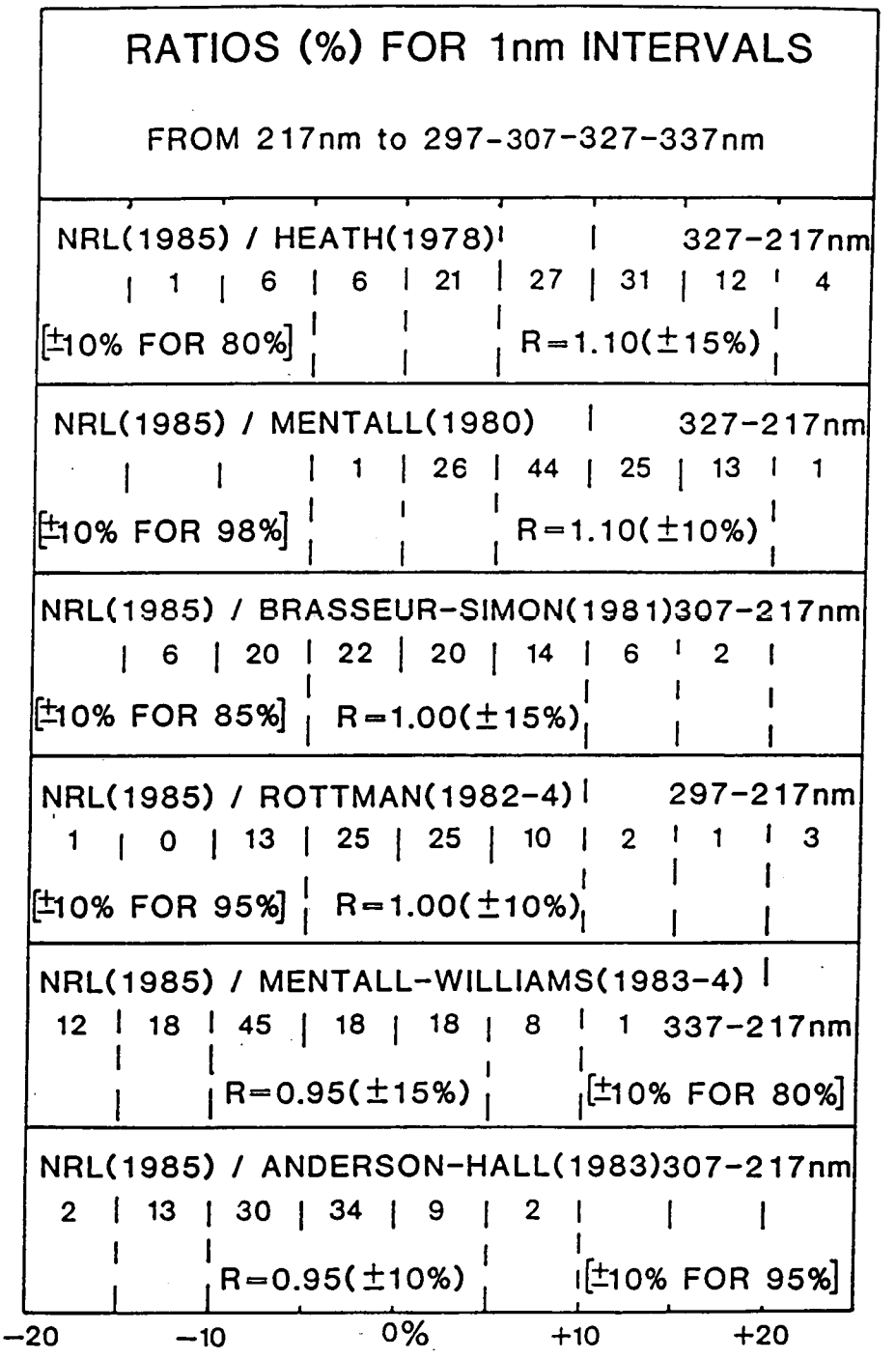

Fig. 31 - Comparison of spectral irradiances between 217 and 337 nm. The reference spectrum is Spacelab 2 - SUSIM for 1 nm intervals.

SUSIM-ROTTMAN, R = 1.00 ± 10% for 95% of the spectral range 217-317 nm.

Thus, the observational results (110 intervals of 1 nm) of Heath and of Mentall et al are systematically 10% lower than the NRL data, with various deviations reaching ± 10% to 15%. The compilation of Brasseur and Simon (90 intervals) and the observational results of Rottman (80 intervals) do not indicate a systematic difference with the NRL data but deviations of the order of ± 10%, respectively. The recent results of Mentall and Williams (120 intervals) and of Anderson and Hall (90 intervals) are systematically 5% higher than the NRL irradiances with deviations of the order of ± 15% or ± 10%, respectively.

In conclusion, in the spectral region 210-330 nm, the comparison of the principal observational results obtained during the last ten years over 500 cm^{-1}, or 1 nmm, intervals indicates that the general accuracy of the irradiances value cannot be better than ± 10%, and that random errors may increase the uncertainty limits by ± 10% to ± 15%. There is agreement with SUSIM (the reference spectrum at ± 5% for 55%, 60%, 50%, 60%, 50% and 70% of the observational results (1 nm intervals) of Heath, Mentall et al., Brasseur and Simon, Rottman, Mentall and Williams, and Anderson and Hall, respectively. The various percentages can be compared with the percentages shown in Fig. 31 for an uncertainty limit of ± 10%, i.e. 80%, 98%, 85%, 95%, 80% and 95% respectively.

The SUSIM results adopted as the reference spectrum are listed in Tables 13 and 14 for 500 cm^{-1} intervals and for 1 nm intervals, respectively. The spectral solar irradiances in 500 cm^{-1} intervals (Table 13) increase from 1.7×10^{12} photons cm^{-2} s^{-1} at 25500-26000 cm^{-1}, i.e. they rise by a factor of 1000 in the 50000-25000 cm^{-1} interval.

Table 14 illustrates the differences which may occur between the results of various analyses of solar irradiances. Thus, in addition to the re-evaluation and interpretation of the various observational data, it is clear that a program of continuing simultaneous measurements of the ultraviolet spectral irradiances is still needed.

TABLE 13.- Solar irradiances in 500 cm^{-1} intervals deduced from Spacelab 2 observations (SUSIM) between 50000 and 25500 cm^{-1}

Wavenumber Interval (cm^{-1} ± 250)	Photons cm^{-2} s^{-1} (500 cm^{-1})	Wavenumber Interval (cm^{-1} ± 250)	Photons cm^{-2} s^{-1} (500 cm^{-1})	Wavenumber Interval (cm^{-1} ± 250)	Photons cm^{-2} s^{-1} (500 cm^{-1})
49750	1.69×10^{12}	41750	1.40×10^{13}	33750	3.60×10^{14}
49250	1.92	41250	2.23	33250	3.46
48750	2.41	40750	2.03	32750	4.76
48250	2.88	40250	2.05	32250	5.31
47750	4.84	39750	1.98	31750	5.96
47250	7.73	39250	2.90	31250	6.55
46750	8.96	38750	5.26	30750	7.89
46250	8.63	38250	4.65	30250	9.47
45750	1.11×10^{13}	37750	1.16×10^{14}	29750	9.06
45250	1.20	37250	1.29	29250	1.01×10^{15}
44750	1.59	36750	1.19	28750	1.08
44250	1.29	36250	1.14	28250	1.22
43750	1.38	35750	0.78	27750	1.26
43250	1.55	35250	1.62	27250	1.68
42750	1.33	34750	2.40	26750	1.61
42250	1.60	34250	3.82	26250	1.77
				25750	1.91

TABLE 14.- Solar irradiances in 1 nm and 5 nm intervals deduced from Spacelab 2 observations (SUSIM) by the Naval Research Laboratory and their ratios with the irradiances listed in the Air Force Geophysical Handbook (1987) between 200 and 300 nm.

Wavelength Interval (nm)	SUSIM Photons (cm^{-2} s^{-1})	Ratio AF NRL	Wavelength Interval (nm)	SUSIM Photons (cm^{-2} s^{-1})	Ratio AF NRL
200-201	7.94×10^{11}	0.79	225-226	5.74×10^{12}	1.21
1 2	8.61	.73	6 7	4.22	1.26
2 3	8.63	.74	7 8	4.18	1.32
3 4	9.97	.76	8 9	5.91	1.50
4 5	1.10×10	.82	9-230	5.14	1.40
200-205	4.71×10^{12}	0.75	225-230	2.52×10^{13}	1.34
205-206	1.16×10^{11}	.79	230-231	6.17×10^{12}	1.12
6 7	1.21	.80	1 2	5.35	1.11
7 8	1.40	.80	2 3	5.87	1.11
8 9	1.60	.79	3 4	4.89	1.11
9-210	2.27	1.13	4 5	4.12	1.18
205-210	7.63×10^{12}	0.90	230-235	2.64×10^{13}	1.12
210-211	3.05×10^{11}	0.89	235-236	6.30×10^{12}	1.08
1 2	3.50	1.01	6 7	5.23	1.18
2 3	3.51	0.84	7 8	6.09	1.01
3 4	3.35	1.14	8 9	4.38	1.22
4 5	4.37	1.10	9-240	5.29	1.11
210-215	1.78×10^{13}	1.00	235-240	2.73×10^{13}	1.11
215-216	3.86×10^{11}	0.97	240-241	4.84×10^{13}	1.05
6 7	3.57	0.97	1 2	6.03	1.16
7 8	3.49	1.06	2 3	8.83	1.06
8 9	5.17	0.98	3 4	7.92	1.07
9-220	5.26	1.06	4 5	7.88	0.98
215-220	2.13×10^{13}	1.01	240-245	3.55×10^{13}	1.06
220-221	5.46×10^{11}	0.99	245-246	6.16×10^{12}	1.05
1 2	3.83	1.09	6 7	6.22	1.07
2 3	5.58	1.04	7 8	7.02	1.07
3 4	7.17	1.11	8 9	5.49	0.99
4 5	6.60	1.07	9-250	7.43	1.10
220-225	2.86×10^{13}	1.07	245-250	3.24×10^{13}	1.06

TABLE 14.- continued

Wavelength Interval (nm)	SUSIM Photons (cm^{-2} s^{-1})	Ratio AF NRL
275-276	2.70×10^{13}	0.79
6 7	3.71	0.86
7 8	3.50	0.99
8 9	2.39	1.04
9-280	1.17	1.14
275-280	1.35×10^{14}	0.93
280-281	1.44×10^{13}	0.91
1 2	3.36	0.86
2 3	4.74	0.85
3 4	5.18	0.85
4 5	3.97	0.85
280-285	1.86×10^{14}	0.87
285-286	2.18×10^{13}	1.04
6 7	5.43	0.86
7 8	5.97	0.77
8 9	5.11	0.87
9-290	7.56	0.85
285-290	2.62×10^{14}	0.85
290-291	10.01×10^{13}	0.81
1 2	9.25	0.83
2 3	7.98	0.86
3 4	8.77	0.84
4 5	7.90	0.88
290-295	4.39×10^{14}	0.84
295-296	9.12×10^{13}	0.75
6 7	7 91	0.93
7 8	8.87	0.69
8 9	6.56	0.98
9-300	8.63	0.75
295-300	4.10×10^{14}	0.81

5. *SOLAR SPECTRAL IRRADIANCES IN THE REGION OF THE O_2 PHOTODISSOCIATION : BETWEEN 240 nm AND 125 nm*

5.1. General Remarks

Retrospective evaluation of spectral irradiances obtained during the last 10 years at wavelengths relevant to the photodissociation of molecular oxygen provides (Nicolet and Kennes, 1988a) an indication of the accuracy and precision of the information available at the present time. In the spectral region of wavelengths less than 175 nm corresponding to the O_2 Schumann-Runge continuum absorbed in the thermosphere, most of the observational results are not reliable, because the general accuracy is of the order of $\pm$ 50 %. In the spectral region 175-200 nm of the Schumann -Runge bands, mainly absorbed in the mesosphere, the uncertainties of all available data are not less than 20 to 30 % and make it impossible to determine the exact effect of solar activity on the O_2 photodissociation rate. The available measurements for the spectral region associated with the O_2 Herzberg continuum, 200-240 nm, that is relevant to the stratosphere have typical limits of uncertainty as much as $\pm$ 10 %, with additional random errors of $\pm$ 10 % for 1 nm intervals. The general accuracy is not yet sufficient to infer the exact portion of the irradiance changes associated with solar variability. Therefore, a consistent reference spectrum for a better assessment must be adopted to describe the complex behavior displayed by the spectral solar irradiances within the various spectral ranges of the photodissociation of O_2.

5.2. The Schumann-Runge continuum

Since almost all oxygen atoms produced by photodissociation of O_2 in the thermosphere move down to heights near the mesopause to become reattached and form oxygen molecules again, the basic aeronomic parameter is the total production of oxygen atoms. The knowledge of the total number of photons ($cm^{-2}s^{-1}$) at wavelengths less than 175 nm (Figs. 32 and 33) is, therefore, required as the basic solar irradiance parameter. It

should lead to a determination of the variations of the upper boundary conditions (number density of oxygen atoms at the mesopause level) which must be related to solar activity conditions. The question of high (1×10^{12} cm^{-2}) or low (1×10^{11} cm^{-2}) atomic oxygen concentration near the peak has not yet been answered (Llewelyn, 1988).

However, it can be concluded from analysis of the various observations, that there is no direct possibility of understanding the differences, because it seems that there is a lack of agreement. The low values of Heroux and Higgins (1977), of the order of 6×10^{12} photons $cm^{-2}s^{-1}$ for low solar activity, correspond to only 50 % of the values deduced from VanHoosier et al. (1987) for almost the same conditions of solar activity (see Table 15). How can a real solar activity effect be deduced when there are unquestionable differences of $\pm$ 50 % ? The conventional value should be $(1.0 \pm 0.5) \times 10^{11}$ photons $cm^{-2}s^{-1}$; this would indicate that the observational accuracy must be improved. On the other hand, the variation with solar activity is not known, but should be less than a factor of 2. The solar irradiances deduced from Spacelab 2 observations (SUSIM) for 1 nm intervals are given in Table 16 ; the total number of photons is 1×10^{12} cm^{-2} s^{-1} between 175 and 160 nm.

In conclusion, a determination of the total thermospheric production of oxygen atoms requires more observations at wavelengths less than 175 nm with better accuracy to fix the maximum atomic oxygen concentration near the mesopause, its variation with solar activity, and its vertical distribution in the thermosphere (Shepherd and Gerdjikova, 1988; McDade and Llewelyn, 1988 ; Hedin, 1988 ; Bird 1988 ; Stegman and Murtagh, 1988 ; Rees and Fuller-Rowell, 1988).

5.3. The Schumann-Runge band region

The spectral region of the Schumann-Runge bands of O_2 (Fig. 34) requires special attention, because the absolute values must be known in order to detect the effect of solar activity. The differences between the various sets of observations should be less than those arising from changes in solar activity.

Table 16 - Solar irradiances in 1 nm intervals deduced from Spacelab 2 observations (SUSIM) between 175 and 122 nm

Wavelength Interval (nm)	SUSIM Photons ($cm^{-2}s^{-1}$)	Photons ($cm^{-2}s^{-1}$) TOTAL	Wavelength Interval (nm)	SUSIM Photons ($cm^{-2}s^{-1}$)	Photons ($cm^{-2}s^{-1}$) TOTAL
122-123	6.00×10^{9}	1.27×10^{12}	150-151	8.13	1.14×10^{12}
123-124	3.53		151-152	8.96	
124-125	2.76		152-153	1.11×10^{10}	
125-126	2.45		153-154	1.24	
126-127	3.71		154-155	1.94	
127-128	1.85		155-156	1.63	
128-129	1.93		156-157	1.80	
129-130	1.76		157-158	1.64	
			158-159	1.58	
			1590-160	1.63	1.0×10^{12}
130-131	1.21×10^{10}	1.25×10^{12}	160-161	1.83	9.96×10^{11}
131-132	2.49×10^{9}		161-162	2.53	
132-133	1.51×10^{9}		162-163	2.45	
133-134	1.37×10^{10}		163-164	2.73	
134-135	1.70×10^{9}		164-165	3.18	
135-136	3.84		165-166	4.94	6.43×10^{11}
136-137	2.52		166-167	3.60	
137-138	2.62		167-168	4.10	
138-139	2.65		168-169	4.68	
139-140	6.53		169-170	6.27	
140-141	5.69	1.20×10^{12}	170-171	7.34	4.07×10^{11}
141-142	3.60		171-172	7.43	
142-143	4.16		172-173	6.08	
143-144	4.67		173-174	8.01	
144-145	4.72		174-175	9.83	
145-146	4.91				
146-147	6.05				
147-148	7.71				
148-149	7.95				
149-150	7.23				

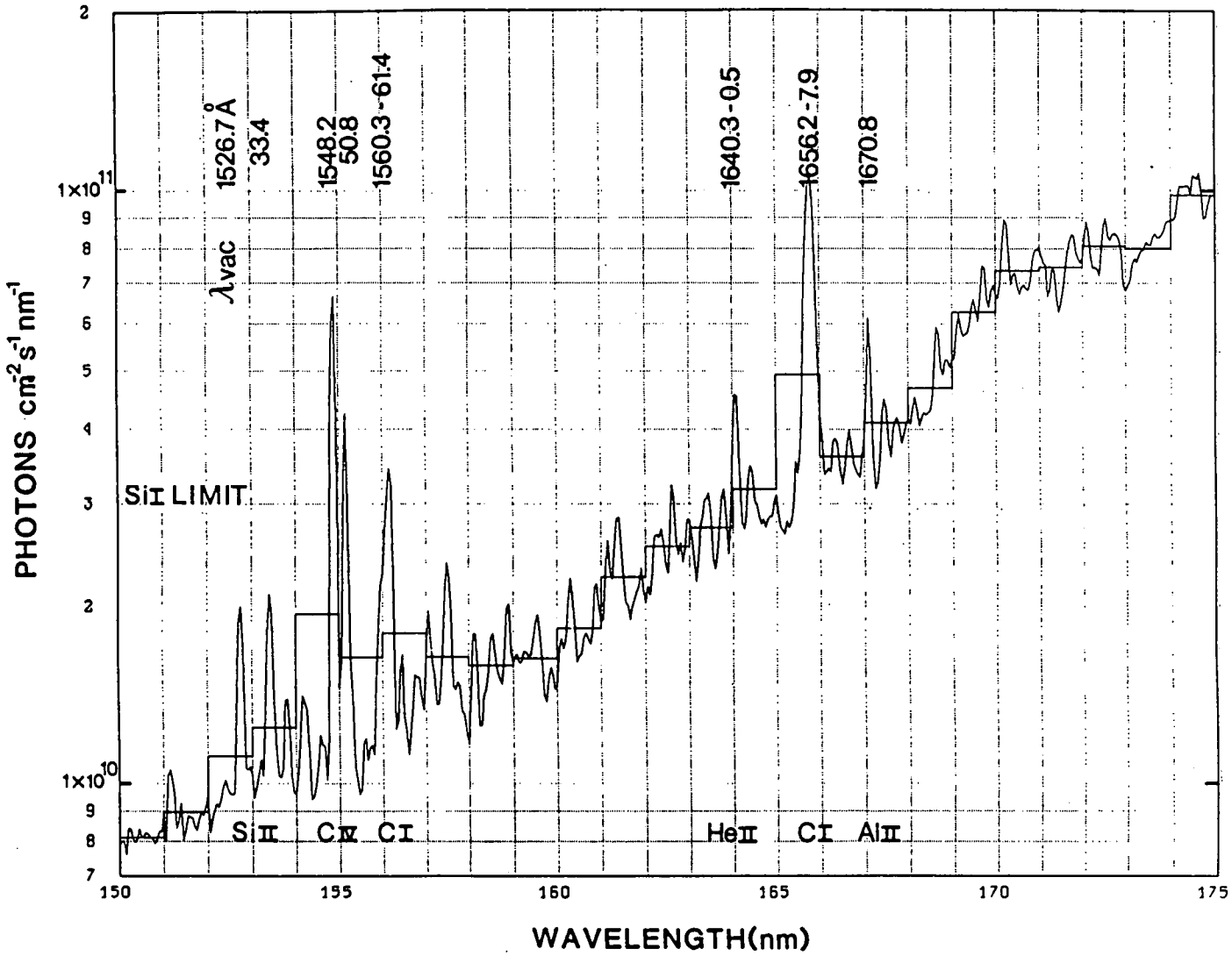

Fig. 32 - Spectral solar irradiances (photons $cm^{-1}s^{-1}nm^{-1}$) from 150 nm to 175 nm. The dashed lines reproduce at each 0.05 nm the irradiances from the SUSIM experiment (VanHoosier et al., 1987) in photons $cm^{-2}s^{-1}$. The solid lines represent averaged values in 1 nm intervals.

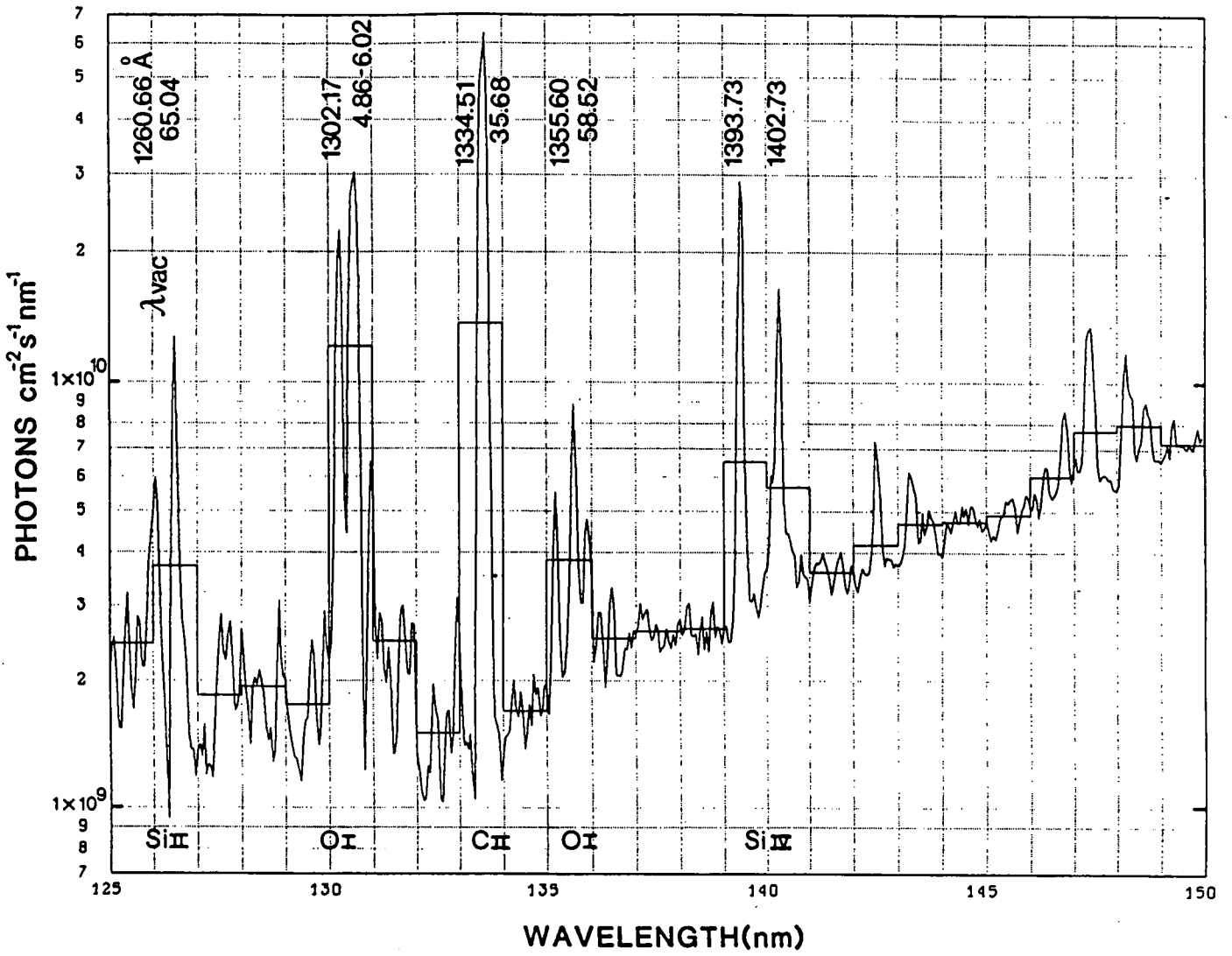

Fig. 33 - Spectral solar irradiances (photons $cm^{-2}s^{-1}nm^{-1}$) from 125 nm to 150 nm. As in Fig. 32.

TABLE 15 - Total number of photons ($Q_\infty cm^{-2}s^{-1}$) in the spectral region of the Schumann-Runge continuum (175-135 nm).

DATE	Solar flux (10.7 cm)	Q_∞	Reference
1951	---	$= 5 \times 10^{11}$	Friedman et al. (1951)
1961	---	$= 2.5 \times 10^{12}$	Detwiler et al. (1961)
1971	---	$= 1.2 \times 10^{12}$	Ackerman (1971)
1981	---	$= 6.5 \times 10^{11}$	Brasseur and Simon (1981
02 Nov. 1973	84	5.7×10^{11}	Heroux and Higgins (1977)
23 Apr. 1974	74	5.2	
13 Dec. 1972	111	6.2	Rottman (1974)
		8.7	Rottman (1981)
30 Aug. 1973	91	6.0	Rottman (1974)
		7.7	Rottman (1981)
28 Jul. 1975	75	8.2	Rottman (1981)
18 Feb. 1976	70	1.0×10^{12}	
9 Mar. 1977	80	1.0	
16 Nov. 1978	132	8.0×10^{11}	Mentall et al. (1985)
5 Jun. 1979	224	1.5×10^{12}	Mount et al. (1980)
22 May 1980	270	8.4×10^{11}	Mentall et al. (1985)
15 Jul. 1980	211	1.4×10^{12}	Mount and Rottman (1981)
16 Oct. 1981	304	6.7×10^{11}	Mentall et al. (1985)
17 May 1982	139	8.0	Mount and Rottman (1983)
23 Jul. 1983	136	7.2	Mount and Rottman (1984)
29 Jul - Aug. 6, 1985	70-85	1.25×10^{12}	VanHoosier et al. (1987)

The reference data (Fig. 35) deduced from the observations by the Naval Research Laboratory (VanHoosier et al., 1987) were made from Spacelab-2 between July 29 and August 6,1985 with the SUSIM, Solar Ultraviolet Spectral Irradiance Monitor. The irradiances measured in the SUSIM experiment can be compared (Figs. 36 and 37) with the values from the compilation of WMO (1985), those of Heath (1980) at high solar activity and those from the compilation of Brasseur and Simon (1981). They are all systematically below the values deduced from SUSIM. The various values of ratios to the NRL data (Nicolet et al., 1988) show that their values deduced from the Brasseur and Simon compilation are of the order of only 0.65 $\pm$ 0.15, from Heath are 0.75 $\pm$ 0.10, and from WMO are 0.85 $\pm$ 0.10. The averaged values of Rottman between 1982 and 1984 correspond to a ratio of 0.80 $\pm$ 0.15 with a minimum near 180 nm. The recent values of Mentall and Williams (1988) in 1983 and 1984 lead to different ratios of 0.75 $\pm$ 0.05 at $\lambda < 188$ nm and of 0.90 $\pm$ 0.05 at $\lambda < 190$ nm. Thus, the photodissociation rates of O_2 in the mesosphere depend, at the present time, more on the adopted solar irradiances (Fig. 37 and Table 17) than on possible solar activity effects that should still be established for individual spectral regions.

5.4. The Herzberg continuum

The uncertainties in the spectral region 200-240 nm (see Table 17) are certainly less than differences occurring at shorter wavelengths. The ratio for 500 cm^{-1} intervals of the values given by Brasseur and Simon to those deduced from the SUSIM data is 0.98 $\pm$ 0.12. The WMO compilation yields an almost identical ratio : 0.97 $\pm$ 0.17. The satellite measurements of Heath in 1978 (high solar activity) are systematically lower than the values deduced from SUSIM data (low solar activity) ; their mean ratio is 0.90 $\pm$ 0.07 and reaches 0.85 $\pm$ 0.05 at $\nu > 48000$ cm^{-1} and 0.95 $\pm$ 0.05 at $\nu < 48000$ cm^{-1}. Finally, the values adopted by Nicolet and Kennes (1986) are 10 % lower than the SUSIM data; with an increase of a factor of 1.1 their ratio becomes 1.0 $\pm$ 0.05.

A more detailed comparison between various averaged values in 1 nm intervals indicates systematic differences illustrated in Fig.38 that are

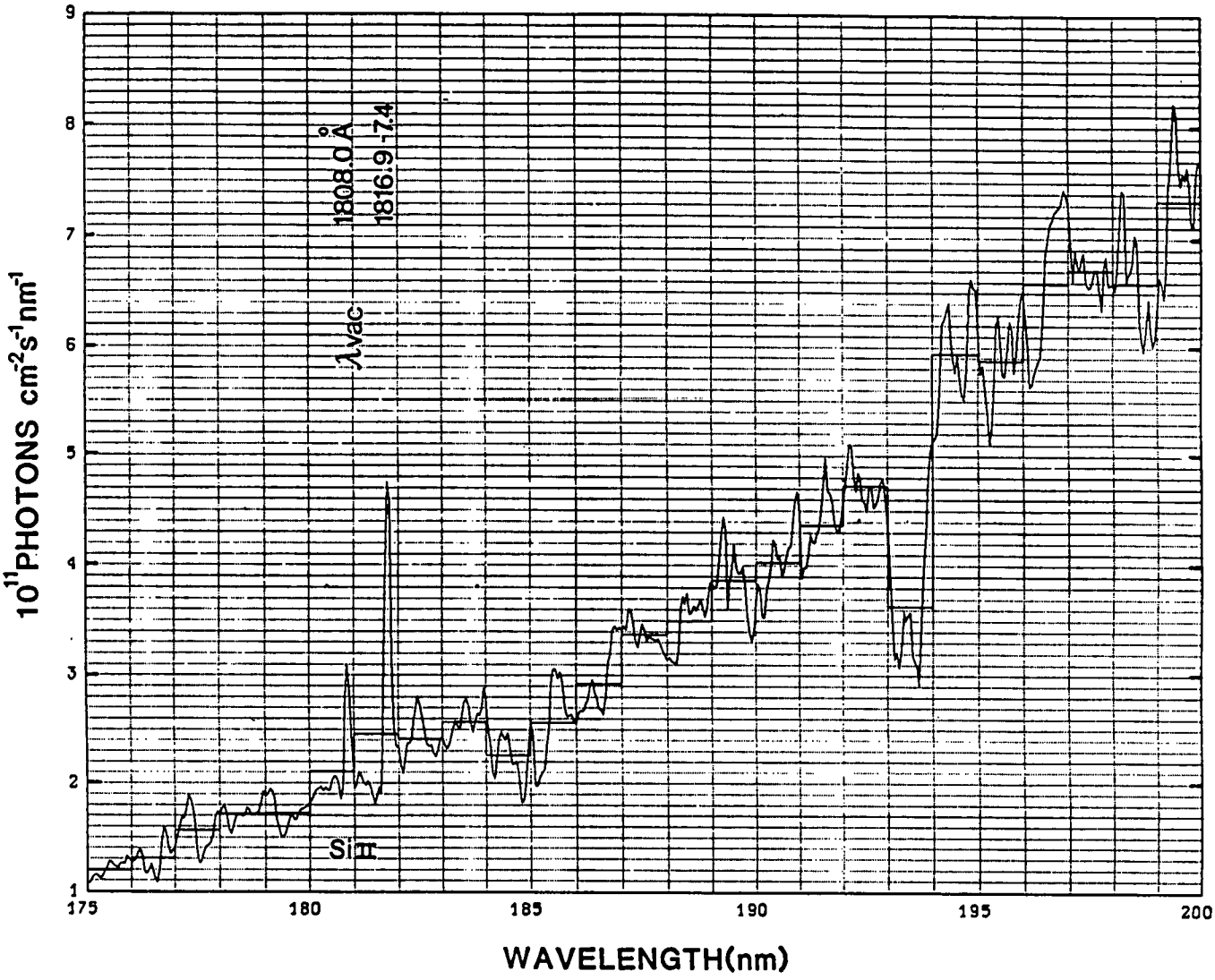

Fig. 34 - Spectral solar irradiances (photons $cm^{-2}s^{-1}nm^{-1}$) from 175 to 200 nm. As in Figs. 32 and 33

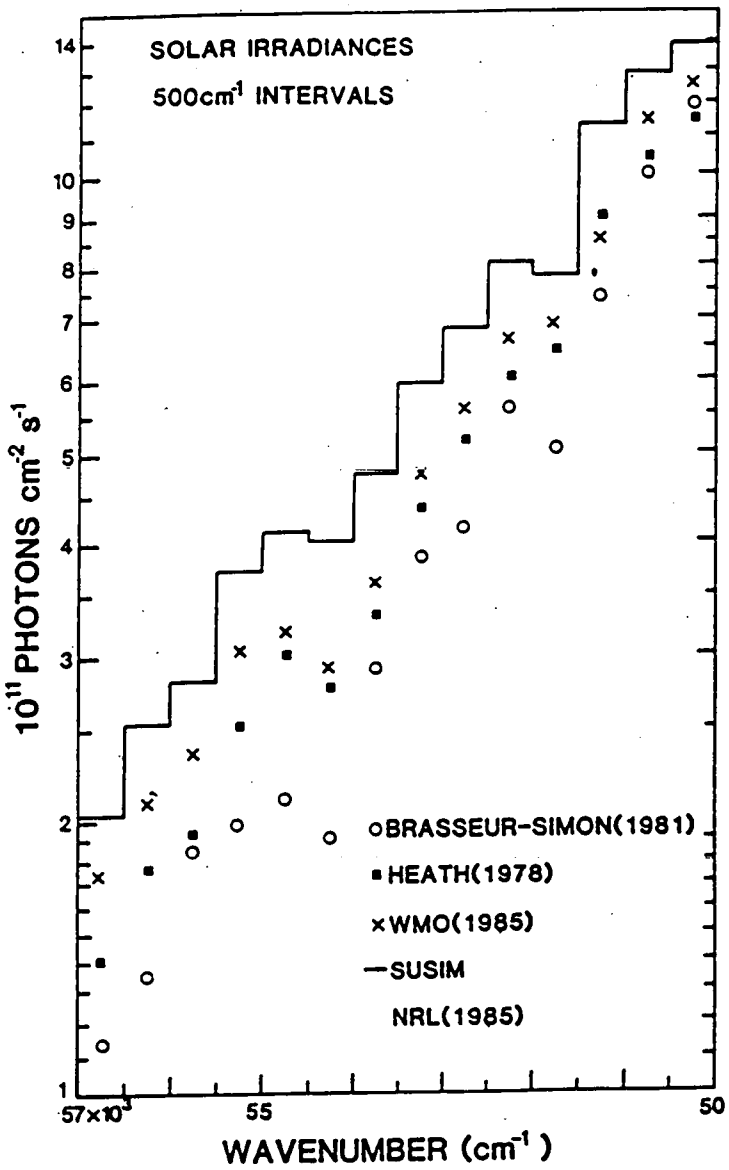

Fig. 35 - Solar spectral irradiances (photons $cm^{-2}s^{-1}$) between 57000 and 50000 cm^{-1} in 500 cm^{-1} intervals

Table 17 - Solar irradiance in 500 cm^{-1} intervals deduced from Spacelab 2 observations (SUSIM), and given in WMO reference solar irradiance (1985).

Wavenumber Interval (cm^{-1})	Wavelength Interval (nm) λ_{vac}	SUSIM Photons $cm^{-2}s^{-1}$ (500 cm^{-1})	WMO Photons $cm^{-2}s^{-1}$ (500 cm^{-1})
57000-56500	175.44-176.99	2.01×10^{11}	1.74×10^{11}
56500-56000	177.00-178.57	2.55	2.10
56000-55500	178.58-180.18	2.83	2.38
55500-55000	180.19-181.81	3.72	3.04
55000-54500	181.82-183.48	4.12	3.19
54500-54000	183.49-185.18	4.04	2.93
54000-53500	185.19-186.91	4.81	3.62
53500-53000	186.92-188.67	5.98	4.73
53000-52500	188.68-190.47	6.88	5.61
52500-52000	190.48-192.30	8.07	6.63
52000-51500	192.31-194.17	7.81	6.90
51500-51000	194.18-196.07	1.14×10^{12}	9.56
51000-50500	196.08-198.01	1.29	1.15×10^{12}
50500-50000	198.02-199.99	1.38	1.27
50000-49500	200.00-202.02	1.69	1.52
49500-49000	202.03-204.08	1.92	1.78
49000-48500	204.09-206.18	2.41	2.20
48500-48000	206.19-208.33	2.88	2.69
48000-47500	208.34-210.52	4.84	4.54
47500-47000	210.53-212.76	7.73	7.14
47000-46500	212.77-215.05	8.96	8.35
46500-46000	215.06-217.39	8.63	8.39
46000-45500	217.40-219.78	1.11×10^{13}	1.08×10^{13}
45500-45000	219.79-222.22	1.20	1.18
45000-44500	222.23-224.71	1.59	1.60
44500-44000	224.72-227.27	1.29	1.34
44000-43500	227.28-229.88	1.38	1.41
43500-43000	229.89-232.65	1.55	1.57
43000-42500	232.56-235.29	1.33	1.38
42500-42000	235.30-238.09	1.60	1.60
42000-41500	238.10-240.96	1.40	1.45
41500-41000	240.97-243.90	2.23	2.20

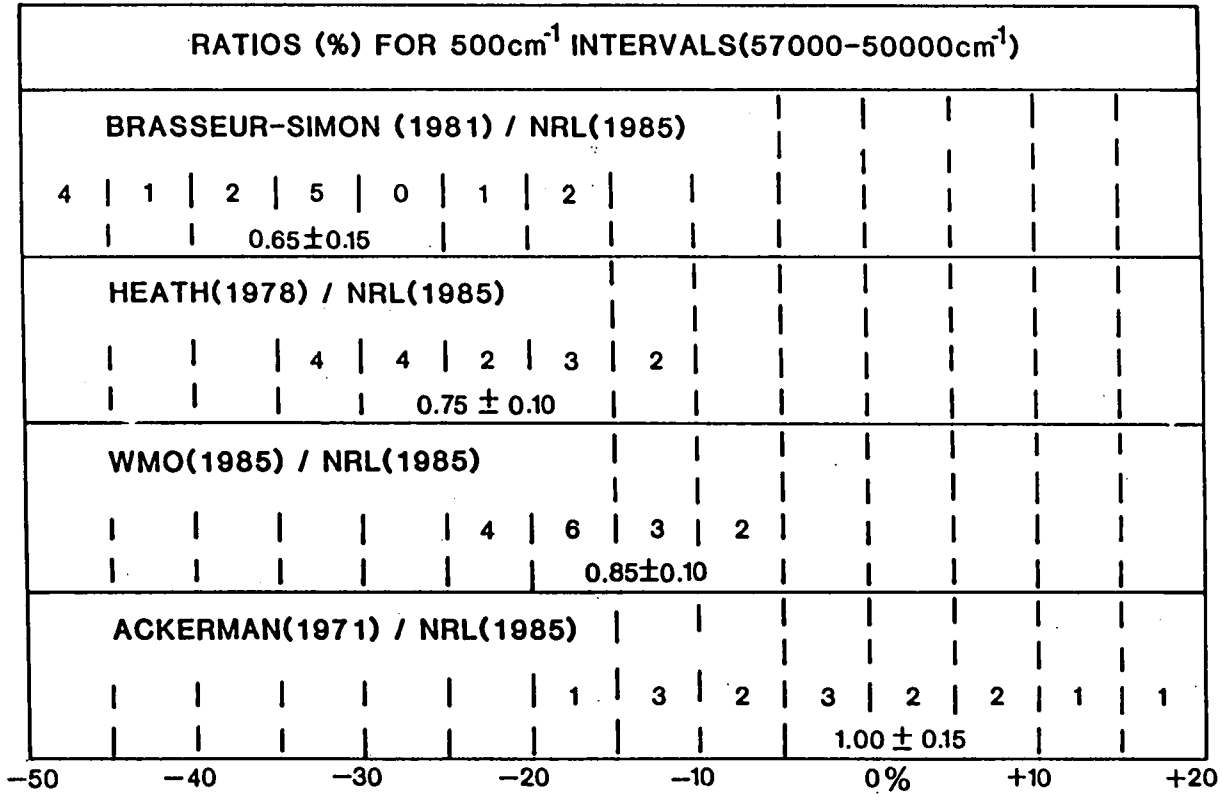

Fig. 36 - Distribution, between 57000 and 50000 cm^{-1}, of ratios of solar irradiances depicted in Fig.1. Numbers of intervals by steps of 5% with the averaged values and their dispersions of the ratios. Reference spectrum : SUSIM.

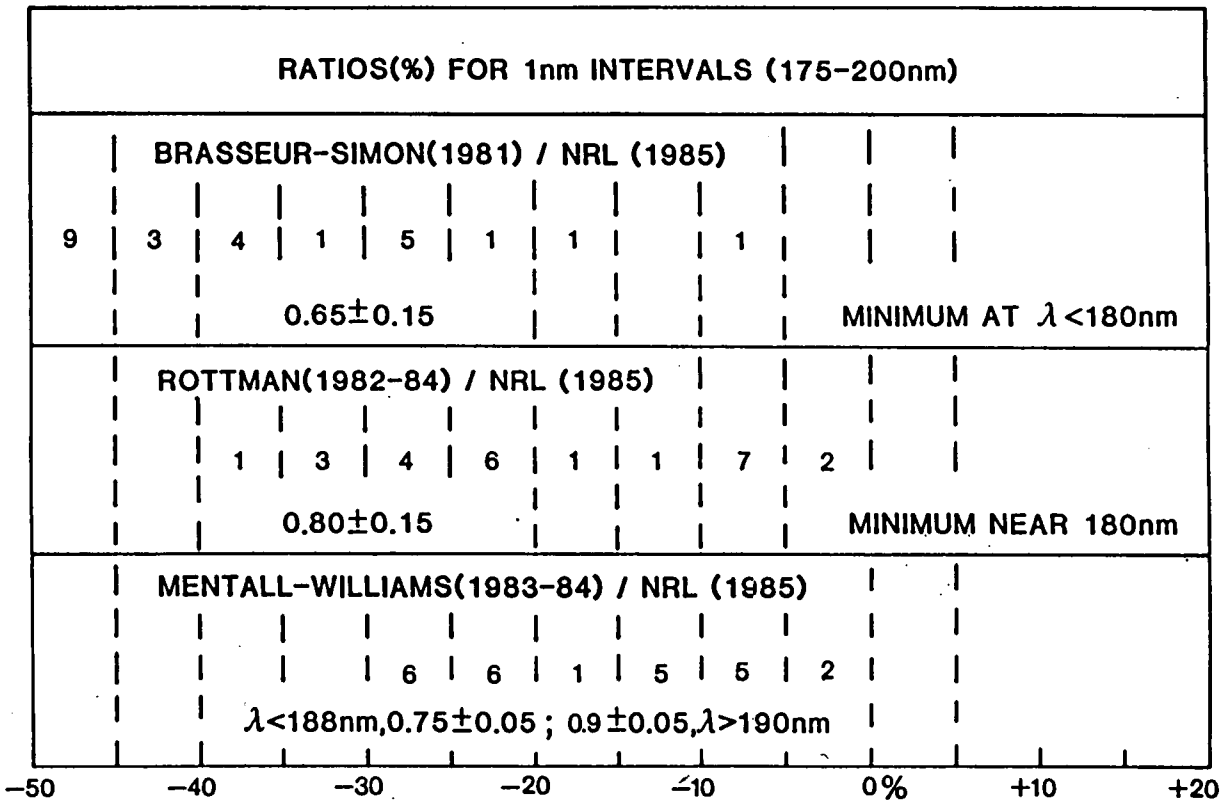

Fig. 37 - Distribution, between 57000 and 50000 cm^{-1} (175-200 nm, of ratios of solar irradiances for 1 nm intervals. Numbers of intervals by steps of 5% with the averaged values and their dispersions of the ratios. Reference spectrum : SUSIM.

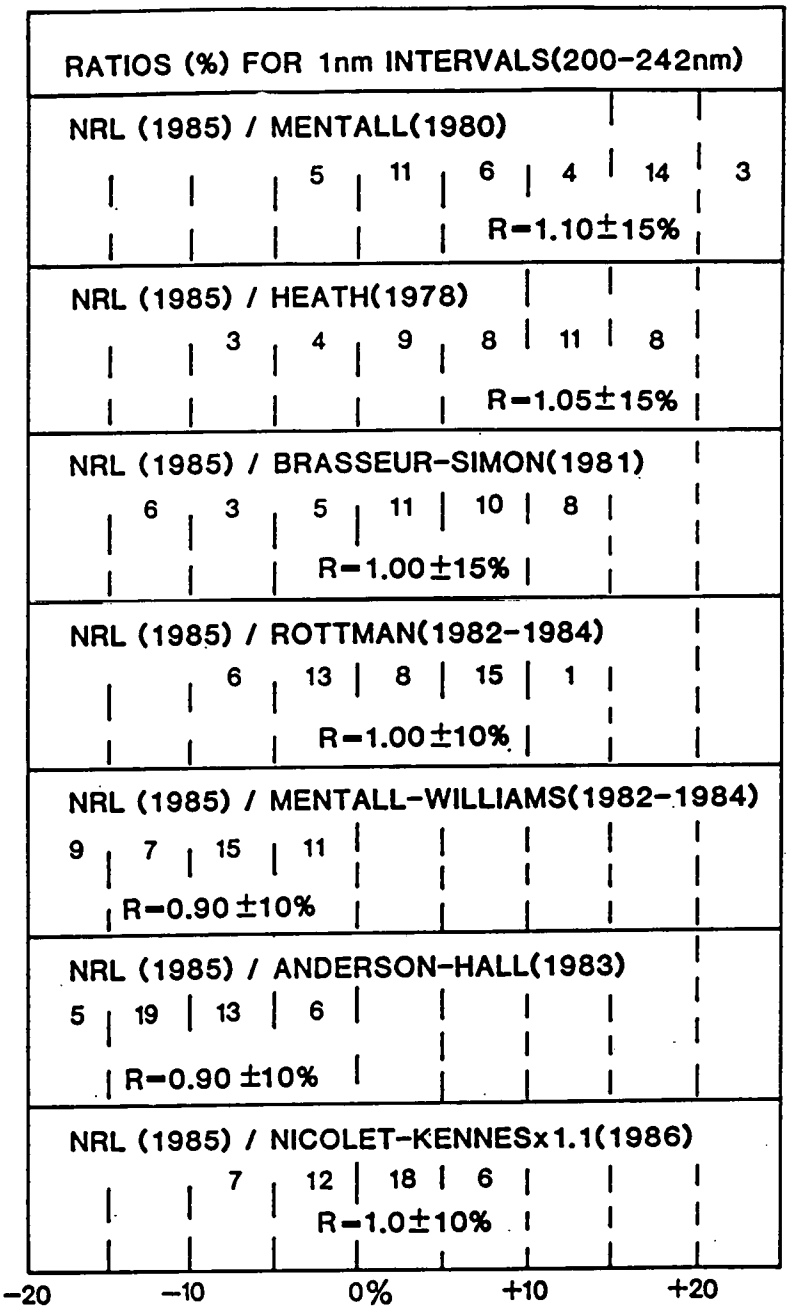

Fig. 38 - Distribution, between 200 and 242 nm, of ratios of solar irradiances for 1 nm intervals. Numbers of intervals by steps of 5 % with the averaged values and their dispersions of the ratios R. Reference spectrum : SUSIM.

as large as ± 10 % with random variations between ± 10 % and ± 15 % if the values averaged over 1 nm intervals deduced from the SUSIM data are again taken as the reference data. However, individual differences in the comparison greater than 10 % should be explicable in terms of wavelength error of the order of 0.1 nm for intervals of 1 nm, because the wavelength scales at some points in the spectrum may be different. It is not easy at low resolution to detect errors, especially when an averaged value of the irradiances is deduced from the complex blends exhibited in the solar spectrum at low resolution. The differences in this spectral region of 0.06 nm to 0.07 nm between the vacuum and air wavelengths must also be considered as sources of possible error in the comparisons between observational data.

A comparison of the reference data with the satellite data of Heath (1980) on November 7, 1978 at relatively high solar activity (solar radio flux at 175 units at 10.7 cm) indicates a ratio NRL/Heath = 1.05 ± 15 %, which are systematically lower values that vary opposite to the solar activity.

Two recent determinations by Mentall and Williams (1988) based on rocket flights on December 7, 1984 (Solar radioflux at 10.7 cm = 102) and on December 10, 1984 (Solar radioflux at 10.7 cm = 77) result in a ratio NRL/Mentall-Williams = 0.90 ± 0.10 ; this is a systematic difference of 10 % with a usual random precision of ± 10 % that is normal when compared on 1 nm intervals. A recent analysis by Anderson and Hall (1988, unpublished) based on observations made at 40 km in April 1983 shows that the ratio NRL/Anderson-Hall corresponds to 0.90 ± 10 %.

In conclusion, in the region of the O_2 Herzberg continuum, 200-240 nm, the absolute accuracy of spectral solar irradiances is confined to ± 10 % if only all recent observations (1978-1988) are considered ; the precision of individual measurements is approximately ± 10 % for averaged values over intervals of 1 nm.

6. *THE SOLAR H LYMAN-ALPHA IRRADIANCE*

The objective of many observations of the Sun (Fig. 39), of terrestrial and planetary atmospheres and of comets has been to study the H Lyman-alpha line at 121.656 nm in all of its aspects. See, for example, Basri et al., 1979 ; Bruner and Parker, 1969 ; Bruner and Rense, 1969 ; Lemaire et al., 1978 ; Prinz, 1973 and 1974 ; Purcell and Tousey, 1960 ; Roussel-Dupré, 1982 and 1983 ; Vidal-Madjar, 1977 ; Fontela et al., 1988. The Lyman-alpha line irradiance is much greater than that of the nearby continuum. Besides causing photoionization of nitric oxide in the mesosphere, Lyman-alpha radiation can also cause photodissociation of H_2O, CH_4, CO_2 and O_2 (Fig. 40a and b) and other molecules. In the terrestrial atmosphere, the Lyman-alpha line can pass through a window between two molecular oxygen bands (Nicolet, 1985). The experimental data (Lewis et al., 1983) permit the determination of the O_2 absorption as a function of the wavelength (Fig. 41). A profile of Lyman-alpha appropriate to aeronomic studies is always a composite profile (Figs. 40 and 41) which represents the whole of the solar disk. The effective width of the line to be used in aeronomic calculations includes the principal central region, but not the distant wings. The useful profile has a width of 0.35 nm and extends from 121.39 nm to 121.73 nm ; the intensity at these limits is only 1 % of that near the centre. Thus, the solar emission corresponds to chromospheric temperatures greater than 10000 K (Fig. 39) and is particularly important above 1000 km up to the transition layer, above 2000 km.

In the terrestrial atmosphere (Nicolet, 1985) the effect of solar Lyman-alpha is related to its absorption by molecular oxygen (Fig. 41).

At temperatures representative of the whole of the mesosphere (170 K to 250 K), the experimental values for the absorption by O_2 of Lyman-alpha radiation in the band 121.550 $\pm$ 0.175 nm lead to the following expression for the mean absorption cross-section $\sigma(O_2)_{\tau = 0}$ for optical depth $\tau = 0$ and $\Delta\lambda = 0.175$ nm.

$$\sigma(O_2)_{\tau=0} = (2.35 \pm 0.01) \times 10^{-20} \text{ cm}^2$$

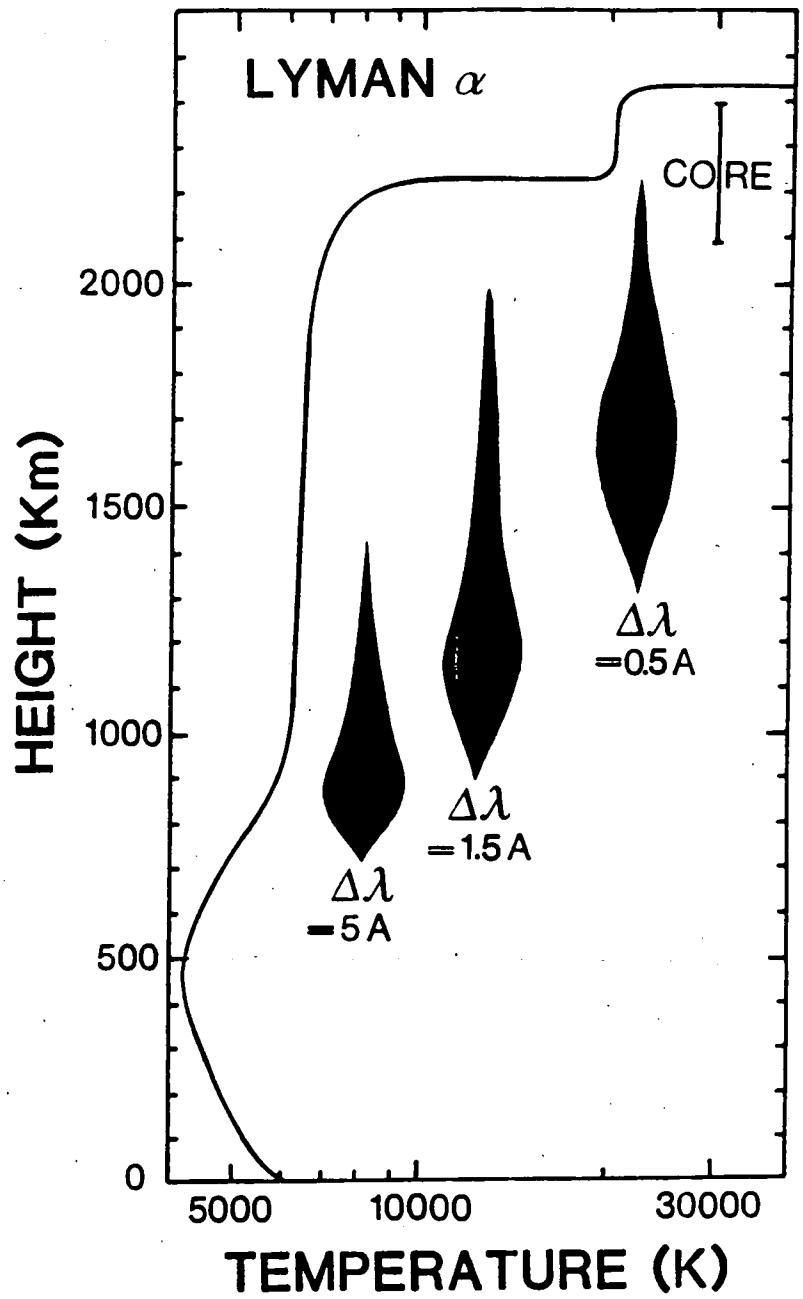

Fig. 39 - Distribution of H Lyman-alpha in the solar chromosphere according to Roussel-Dupré (1982 and 1983).

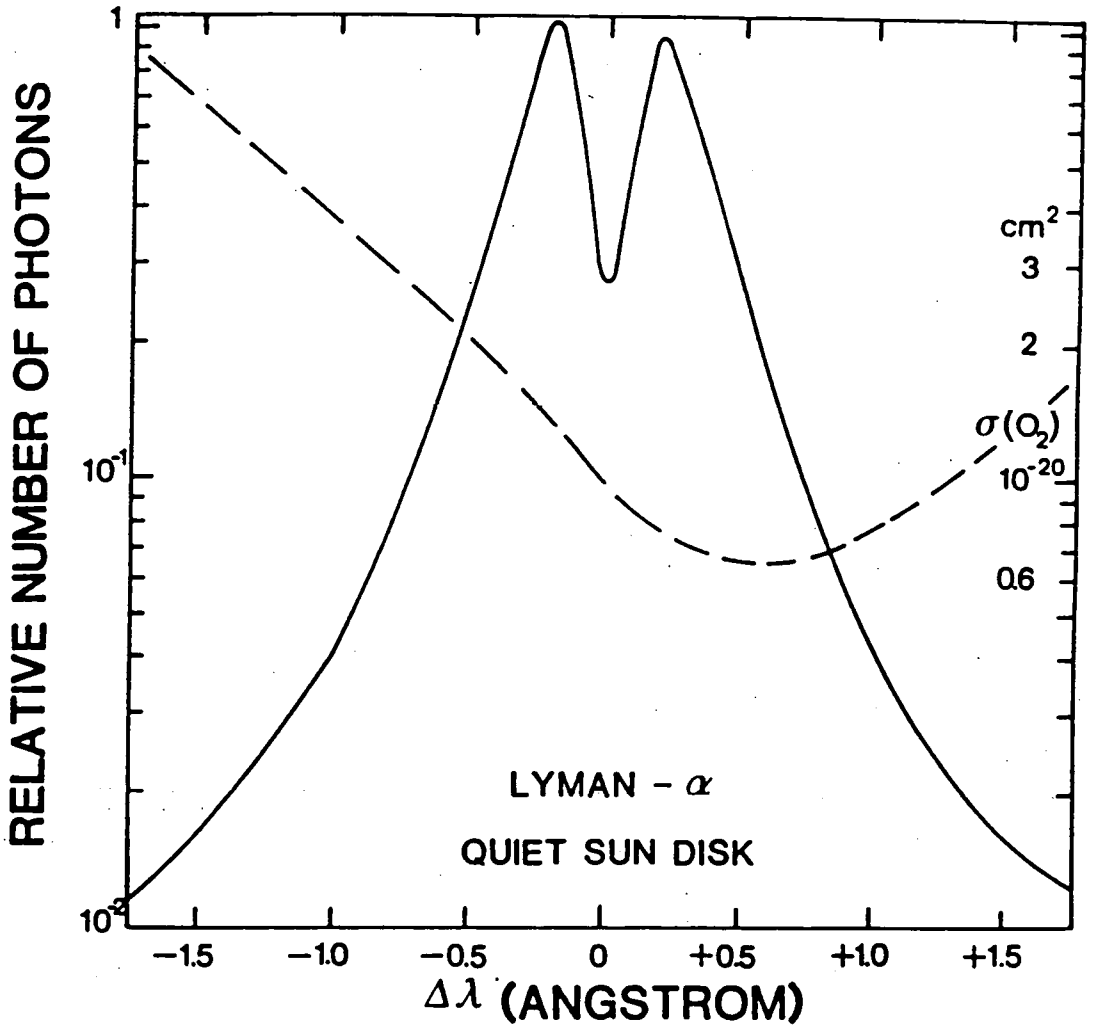

Fig. 40a - Mean profile of the solar H Lyman-alpha line ($\Delta\lambda$ = 3.5 A), for the full disk as seen from the Earth, adopted for the calculation. The corresponding variation of the O_2 absorption cross section at T = 203 K, according to Lewis et al. (1983), is also given. The number of photons q(Lyα) varies by a factor of 100, and $\sigma(O_2)$ by a factor of 10.

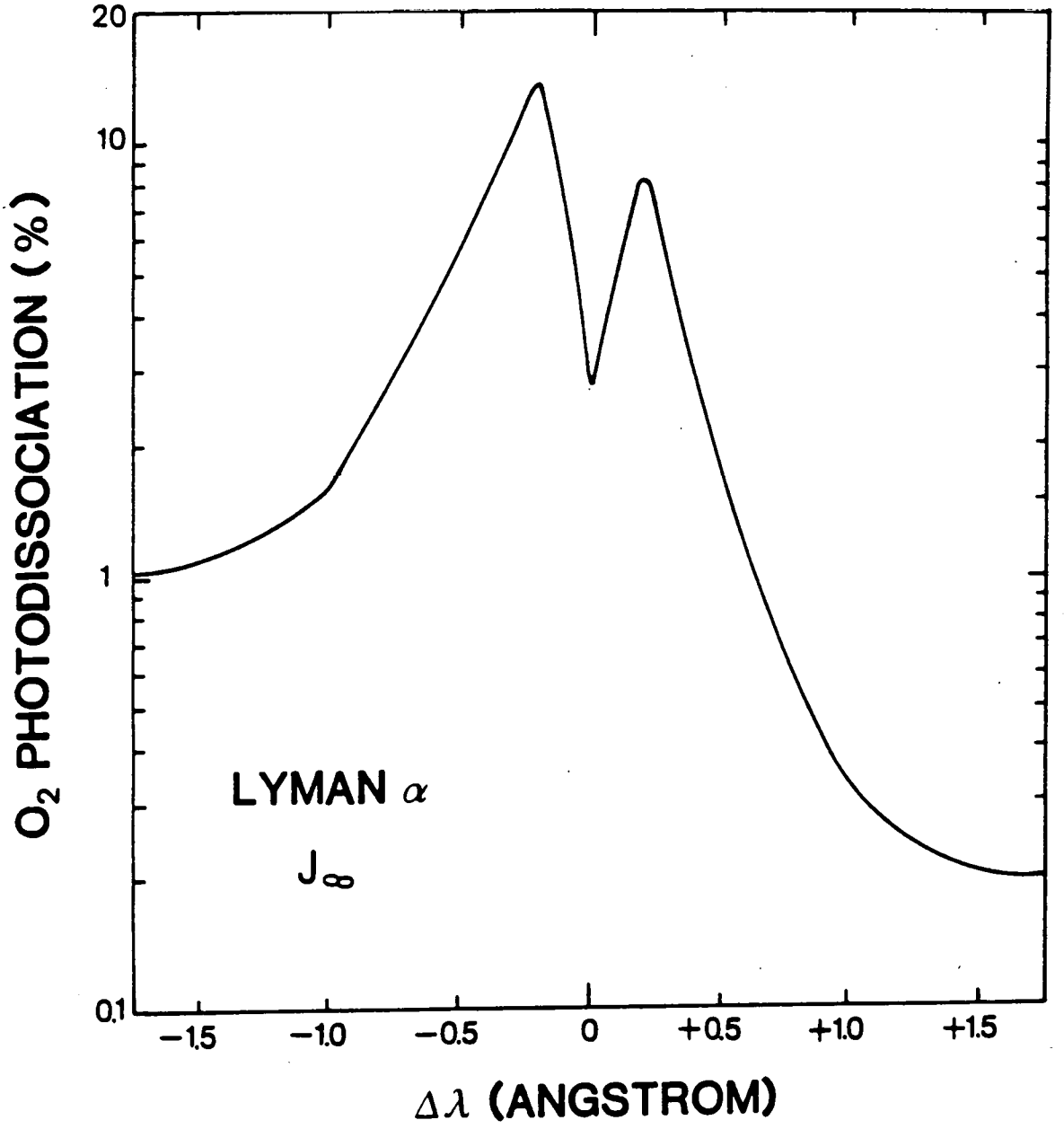

Fig. 40b - Structure of the photodissociation frequency of molecular oxygen at solar H Lyman-alpha indicating the effect of the variation with wavelength of the absorption cross-section of O_2.

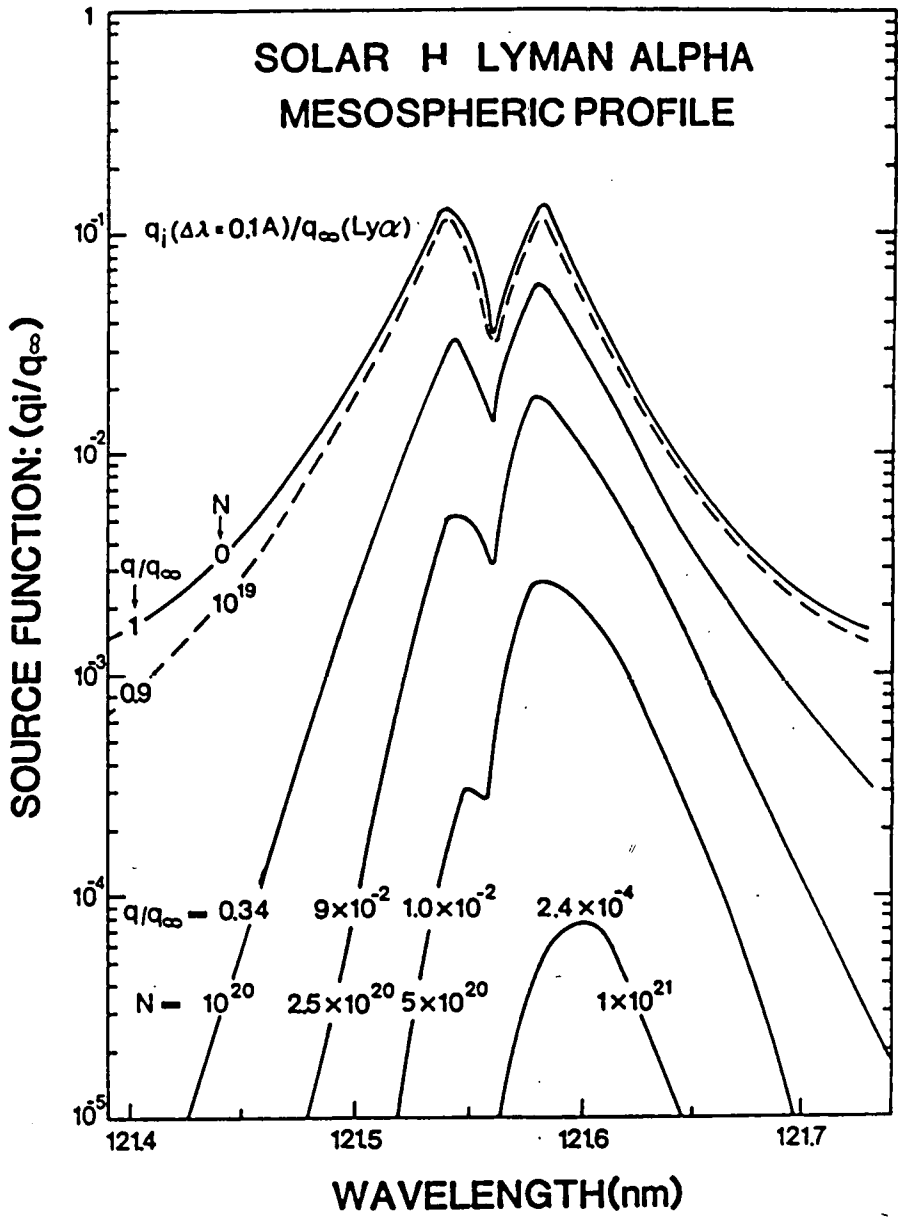

Fig. 41 - The variation (and deformation) of the profile of the solar H Lyman-alpha line, i.e. of the source function defined by $q_{i,Ly\alpha}(\Delta\lambda = 0.1\ A)/q_{\infty,Ly\alpha}(\Delta\lambda = 3.5\ A)$, with increasing number N of O_2 absorbing molecules : (q = number of photons $cm^{-2}s^{-1}$). Six curves are shown for N = 0, 10^{19}, 10^{20}, 2.2×10^{20}, 5×10^{20} and 10^{21} cm^{-2}. Approximate values of the effective transmittance of the H Lyman-alpha irradiances, i.e. the ratio $q(Ly\alpha)/q_{\infty}(Ly\alpha)$, are also given for the various profiles.

where 2.35 is adapted to the temperature 230 K : the value assumed to be the mean temperature for the mesosphere, which is used here as the reference temperature. The results of a detailed calculation are illustrated by various curves in Figure 41. It can be seen that there is a continuous deformation of the solar H Lyman-alpha profile due to the differences in the absorption of O_2 molecules at various wavelengths. The maximum of the emission is displaced towards 121.6 nm where the O_2 absorption cross section is least. It is important to note also that the transmittance decreases by a factor of about 10^4 when the number of O_2 molecules (N) increases from 10^{19} to 10^{21} cm^{-2}. The adoption of a reference temperature of 230 K, adjusted by $\pm$ 20 K for $10^{20} < N < 10^{21}$ cm^{-2}, leads to the following simple expression for the mesospheric transmittance $T_{O_2}(Ly\alpha)$ of solar H Lymn-alpha, the accuracy of which is better than $\pm$ 2%.

$$T_{O_2}(Ly\alpha) = q(Ly\alpha)/q_\infty(Ly\alpha) = \exp\,[-\,2.115 \times 10^{-18}\, N^{0.885}]$$

Figure 42 shows how the effective optical depth $\tau_q(Ly\alpha)$ increases from 0.1 to 10 as the number of O_2 absorbing molecules increases from 10^{19} to 10^{21} cm^{-2}. The corresponding effective O_2 absorption cross-section decreases from $(2.17 \pm 0.01) \times 10^{-20}$ cm^2 at N = 0 to $(1.24 \pm 0.01) \times 10^{-20}$ cm^2 at $N = 10^{19}$ cm^{-2}, and to $(1.09 \pm 0.02) \times 10^{-20}$ cm^2 at $N = 10^{20}$ cm^{-2} corresponding to about unit optical depth (see Figure 41).

Another interesting and important aspect of the action of solar H Lyman-alpha is the photodissociation of water vapour in the various planetary atmospheres and comets. The energetically possible channels leading to the photodissociation of H_2O at wavelengths greater than 100 nm can be considered as follows (see, for example, Nicolet, 1984)

$(J_{H_2\text{-}O})$; $H_2O \rightarrow H_2(X^1\Sigma_g^+) + O(^3P)$ - 486kJ mol^{-1}, i.e. $\lambda < 246$ nm (a)

$(J_{OH\text{-}H})$; $H_2O \rightarrow OH(X^2\Pi) + H(^2S)$ - 494 kJ mol^{-1}, i.e. $\lambda < 242$ nm (b)

$(J_{H_2\text{-}O^*})$; $H_2O \rightarrow H_2(X^1\Sigma_g^+) + (O(^1D)$ at $\lambda < 176$ nm (c)

$(J_{OH^*\text{-}H})$; $H_2O \rightarrow OH(A^2\Sigma^+) + H(^2S)$ at $\lambda < 136$ nm (d)

(J_{H-H-O}); $H_2O \rightarrow O(^3P) + 2H(^2S)$ at $\lambda < 130$ nm (e)

$(J_{H_2-O^{**}})$; $H_2O \rightarrow H_2(X^1\Sigma_g^+) + O(^1S)$ at $\lambda < 130$ nm (f)

The analysis of all the experimental data (Nicolet, 1984) shows that the following processes must be considered at Lyman-alpha :

(J_{OH-H}) ;

$$H_2O + h\nu(\text{Lyman } \alpha) \rightarrow OH(X^2\Pi) + H(^2S) \quad 70\ \%$$

(J_{OH^*-H}) ; $\rightarrow OH(A^2\Sigma^+) + H(^2S)$ 8 %

(J_{H_2-O}) ; $\rightarrow H_2(X^1\Sigma_g^+) + O(^1D)$ 10 %

(J_{H-H-O}) ; $\rightarrow O(^3P) + 2H(^2S)$ $\overline{12}$ %

The values that have been adopted here for the various yields are based on the most recent laboratory measurements with an uncertainty estimated to be less than 10 %. Thus, the production of molecular hydrogen should correspond to 10 % of the total photodissociation and atomic hydrogen to 102 %. A detailed calculation (Nicolet, 1984) indicates that the mean absorption cross-section at Lyman-alpha (Fig.43) for H_2O, 1.5×10^{-17} cm^2, can be adopted.

In aeronomic work the knowledge of the absolute value of the Lyman-alpha irradiance is required and its variation during the solar cycle must be clearly understood. This question was discussed in the introduction and there is not yet a final solution. If we assume extreme limits (based on all accepted observations) for the absolute value of the Lyman-alpha irradiance for a very quiet Sun (minimum of the solar cycle) the number of photons (q_∞) at the top of the earth's magnetosphere would be

$$q_\infty(Ly\alpha)_{\text{quiet sun}} = (2.5 \pm 0.5) \times 10^{11} \text{ photons cm}^{-2}\text{s}^{-1}$$

within an accuracy of $\pm$ 20 %. If we try to follow a certain group of observational values, it is possible to write

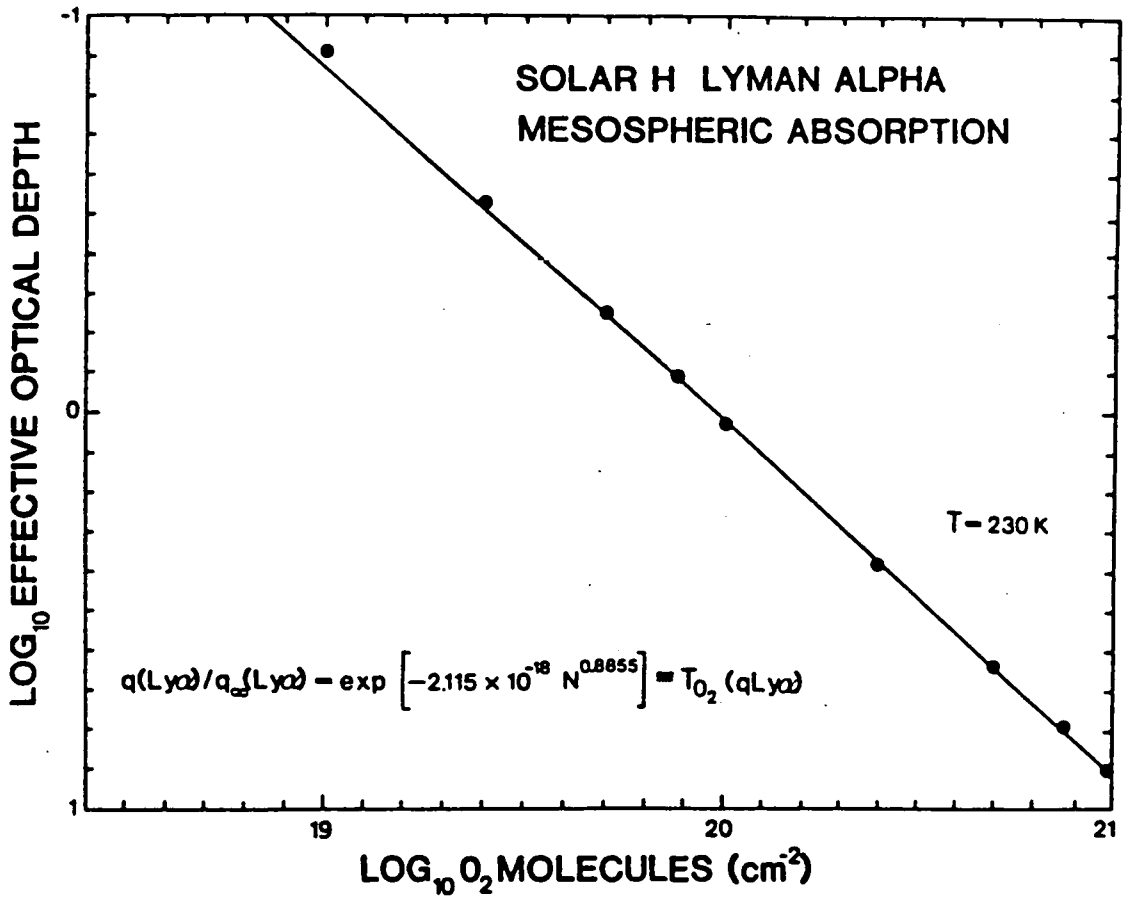

Fig. 42 - Mesospheric absorption of the solar H Lyman-alpha line (number of photons $cm^{-2}s^{-1}$) represented by its effective optical depth (O_2 molecules at T = 230 K) for values of $\tau_{q(Ly\alpha)}$ between 0.1 and 10. The unit effective optical depth $\tau_q(Ly\alpha) = 1$ is reached near $N = 10^{20}$ O_2 molecules cm^{-2} and rises to about $\tau_q(Ly\alpha) = 8$ at $N = 10^{21}$ cm^{-2}. The line is obtained from the formula $T_{O_2}(Ly\alpha)$ for T = 230 K.

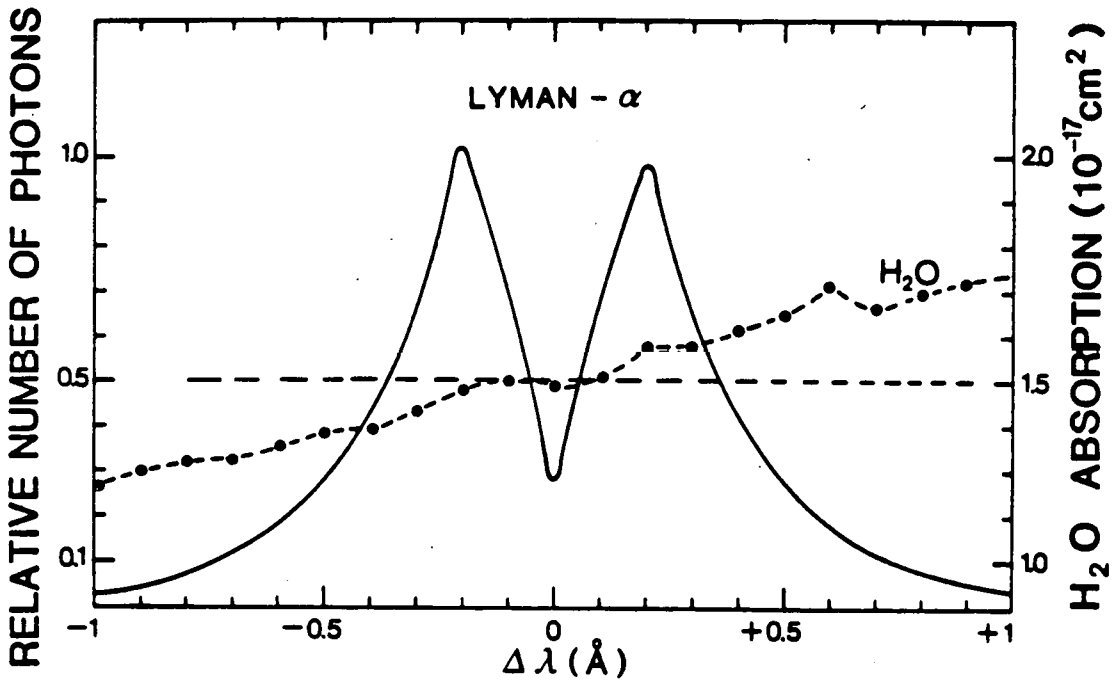

Fig. 43 - The absorption cross-section of H_2O, according to Lewis et al. (1983) (dashed line) and the profile of solar H Lyman-alpha (full line).

$$q_\infty(Ly\alpha)_{quiet\ sun} = (2.25 \pm 0.25) \times 10^{11} \text{ photons cm}^{-2}\text{s}^{-1}$$

with an accuracy of the order of $\pm$ 10 %. As far as the solar activity is concerned, its effects would be given by the following formula :

$$q_\infty(Ly\alpha) = q_\infty(Ly\alpha)_{quiet\ sun} \quad 1 + (0.3 \pm 0.1) \frac{F_{10.7} - 65}{100}$$

where $F_{10.7}$ is the solar radioflux at 2800 MHz published by the National Research Council in Ottawa and used here as the index of solar activity if 65 is the minimum value for a very quiet sun (see Bossy, 1983 ; Bossy and Nicolet, 1981 ; Nicolet, 1981 ; 1983a and b).

The daily solar radioflux values at 2800 MHz have been compared (Nicolet and Bossy, 1985) with the fluxes obtained at Toyokawa at 9400, 3750, 2000 and 1000 MHz between 1957 and 1983. The results of a detailed study of over 8000 daily values provided a basis for testing the stability of the data with respect to time and solar activity, and have led to the conclusion that various trends corresponding to drifts of specific origin may occur. However, a three-dimensional square line representing the fluxes at 3,8 and 10.7 cm can be determined which corresponds to the correct two-dimensional relations between 3 and 8 cm, 3 and 10.7 cm, and 8 and 10.7 cm. Thus, the combination of the radiofluxes at 3, 8 and 10 cm forms a good basis for a permanent solar activity index based on solar radio emission in the centimetre band.

In the preceding formula the coefficient 0.3 is introduced with a precision of only 30 %, which corresponds to extreme values ; 0.2 would be the minimum value to be adopted if Lyman-alpha strictly follows a minimum variation as defined by the variation of the solar radiofluxes with solar activity and 0.4 would correspond to the maximum possible value of the Lyman-alpha irradiance with inclusion of real or spurious anomalies. The maximum coefficient 0.4 necessitates introduction of quadratic relationships in place of linear expressions to cover various trends corresponding to drifts of all origins.

7. *CONCLUSIONS*

High-precision measurements of the solar spectral irradiances in the visible UV and EUV are extremely arduous, fastidious, obscure and complex. The necessity of determining correct irradiances requires more laboratory calibrations, more simultaneous measurements with different instruments, and more continuous observations. It is clear that the scientific groups trying to improve this basic parameter for the study of planetary atmospheres and comets have not yet received the minimum support which is needed. It is also clear that many exceptional reported features are instrumental effects that may be usual in a stellar spectra bank and cannot always be detected. Nevertheless, we must note that it is always possible that relevant solar irradiance routine can be developed to distinguish between good and bad data if the unsatisfactory conditions of observation liable to cause misinterpretation are avoided through the provision of increasing suppport from the various space agencies.

Finally, the reference spectra (SUSIM from 120 nm to 400 nm and Arvesen et al. from 350 nm to 900 nm) adopted here show clearly where are the fundamental differences are, and where the quality of the observations must be improved.

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