ULTRAVIOLET SOLAR RADIATION RELATED TO MESOSPHERIC PROCESSES

M. ACKERMAN
Institut d'Aéronomie Spatiale de Belgique, Brussels, Belgium

1. Introduction

The atmospheric layer of strong negative temperature gradient called the mesosphere and located at altitudes between roughly 50 and 85 km is still part of the homosphere since the mean molecular mass is there maintained constant at all altitudes by the mixing of the major constituents. However, the chemical reactions are very efficient in this region and strongly affect the concentration of minor constituents. These processes are of course not strictly limited in altitude and continue to play a role in the neighbouring atmospheric regions, namely the stratosphere below and the thermosphere above, by transport processes.

These interferences lead to some difficulties in defining the solar ultraviolet radiation of interest to the mesosphere where the solar photons of sufficient energy to initiate chemical chain reactions, penetrate with different degrees of attenuation. The two main absorbing species involved in this attenuation are molecular oxygen and ozone of which the photodissociation produces atomic oxygen, providing the main oxidizing agent in the chemosphere. Typical total numbers of molecules above 50 and 85 km are respectively 4×10^{21} cm^{-2} and 2×10^{19} cm^{-2} for O_2 and 10^{17} cm^{-2} and 10^{13} cm^{-2} for O_3. Since maximum absorption cross sections are of the order of 10^{-17} cm^2, oxygen and to a lesser degree ozone will control the penetration of solar ultraviolet radiation in the mesosphere.

The data actually available on the solar ultraviolet flux from 1100 Å to 3500 Å will be discussed here. The short wavelength limit will allow inclusion of the Lyman α radiation which plays a role in the photodissociation of O_2, H_2O, CO_2, etc., and which constitutes the bridge between the chemosphere and the ionosphere owing to its important role in the formation of the *D* region by ionizing nitric oxide. The long wavelength limit has been fixed at the beginning of the ultraviolet absorption of ozone in the Huggins bands.

On the other hand, to allow the evaluation of the number of photons available at different altitudes, absorption cross section data on O_2 and O_3 will be discussed.

Finally, adopted values for the three parameters will be listed for fixed wavelength intervals suitable for photochemical computations.

2. Absorption Cross Section of Ozone

Between 3500 Å and 2000 Å, ozone absorbs in a wide band discovered by Hartley and peaking near 2500 Å. At this wavelength, unit optical depth for a typical ozone

Fiocco (ed.), Mesospheric Models and Related Experiments, 149–159.

distribution takes place at the lower boundary of the mesosphere for an overhead Sun and at 70 km for a solar zenith distance of 90°. This indicates the important mesospheric role of the Hartley band of ozone which has a bell shape presenting a diffuse structure corresponding to a complicated set of diffuse bands. On the long wavelength side, between 3100 Å and 3500 Å, the structure appears more clearly and was discovered by Huggins in the spectrum of Sirius near the horizon.

The photodissociation of ozone may lead to molecular and atomic oxygen in various excited states, as was already pointed out more than 30 years ago by Nicolet (1939). The absorption cross section of ozone has been well known since the work of Vigroux (1953), Watanabe *et al.* (1953) and Inn and Tanaka (1953). A slight disagreement between the values given by Vigroux (1953) and Inn and Tanaka (1953) at wavelengths smaller than 2700 Å prompted the measurements of Hearn (1961). These have been confirmed by Griggs (1968). New measurements of Vigroux (1969) have definitely shown the correctness of the data of Inn and Tanaka (1953). Various sets of data are represented in Figure 1. Below 2000 Å, only one set of data exists to our knowledge, that of Watanabe *et al.* (1953). Below 1800 Å ozone has so far not been shown to play a role, either in the photochemistry or in the transparency of the Earth atmosphere,

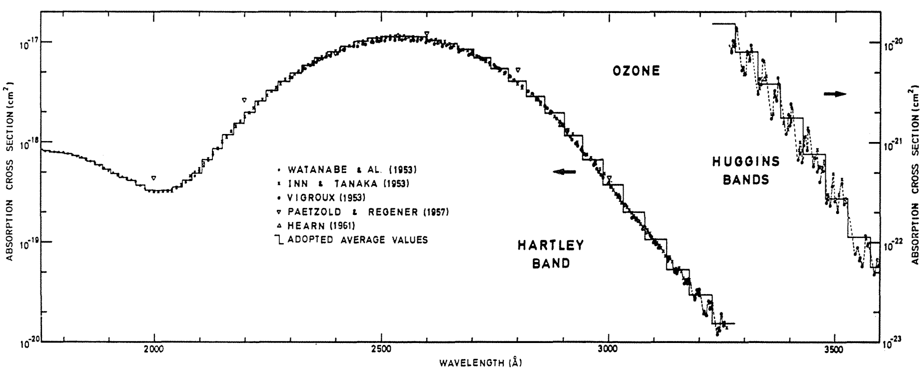

Fig. 1. Absorption cross section of ozone vs wavelength in the Hartley and Huggins bands.

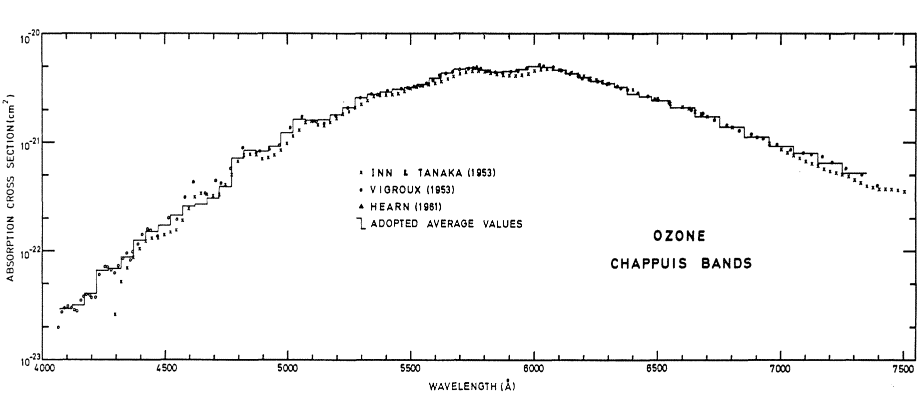

Fig. 2. Absorption cross section of ozone vs wavelength in the Chappuis bands.

since oxygen is there the main absorbant and since the solar ultraviolet intensity is so small compared to that in the 2000 to 3500 Å region.

For the sake of completeness, absorption cross section values in the Chappuis bands are represented in Figure 2.

It appears that absorption cross sections of ozone are now very well known. However, the question about the quantum yield of the various photodissociation processes is not yet fully answered.

3. Absorption Cross Section of Molecular Oxygen

Many data exist on the absorption cross section of molecular oxygen. A critical analysis is necessary before adopting useful aeronomic values. This was done several times in the past, by Nicolet and Mange (1954) for instance. Many new measurements have been made in the last few years which justify a new analysis. This will be made for successive wavelength intervals.

1160 Å–1370 Å. The absorption by molecular oxygen changes rapidly with wavelength in this region, presenting optical windows that allow the penetration of the solar radiation in the mesosphere. Absorption cross sections have for instance been obtained by Watanabe *et al.* (1953, 1958). One optical window which is particularly well known for its fundamental importance in mesospheric problems allows the deep penetration of the solar Lyman α radiation. Values of absorption cross section of O_2 at 1215.67 Å have been obtained by various authors (Preston, 1940; Watanabe *et al.*, 1953; Ditchburn *et al.*, 1954; Lee, 1955; Watanabe *et al.*, 1958; Metzger and Cook, 1964; Ogawa, 1968; and Gailly, 1969) and range from 8.5×10^{-21} to 1.04×10^{-20} cm^2. This leads to unit optical atmospheric depth at about 75 km altitude for an overhead sun. The Lyman α line has been shown to be slightly on the short wavelength wing of the optical window and pressure effects on the absorption have not yet been satisfactorily interpreted.

1370 Å–1750 Å. This region is characterized by the Schumann-Runge continuum which presents high values of the absorption cross section measured by various authors (Landenburg and Van Voorhis, 1933; Schneider, 1940; Ditchburn and Heddle, 1953; Watanabe and Marmo, 1956; Huffman *et al.*, 1964; Metzger and Cook 1964; Hudson *et al.*, 1966) as shown in Figure 3, leading to a complete extinction of the solar radiation in the thermosphere.

1750 Å–2431 Å. Many absorption cross section values discussed recently by Ackerman *et al.* (1970) have been obtained since the beginning of this century for the Schumann-Runge bands of O_2 which extend from 1750 Å to 2000 Å. While they indicate the important role that the bands can play in the mesospheric photochemistry, they are not very valuable for precise aeronomical evaluations.

This situation has recently been considerably improved. New laboratory measure-

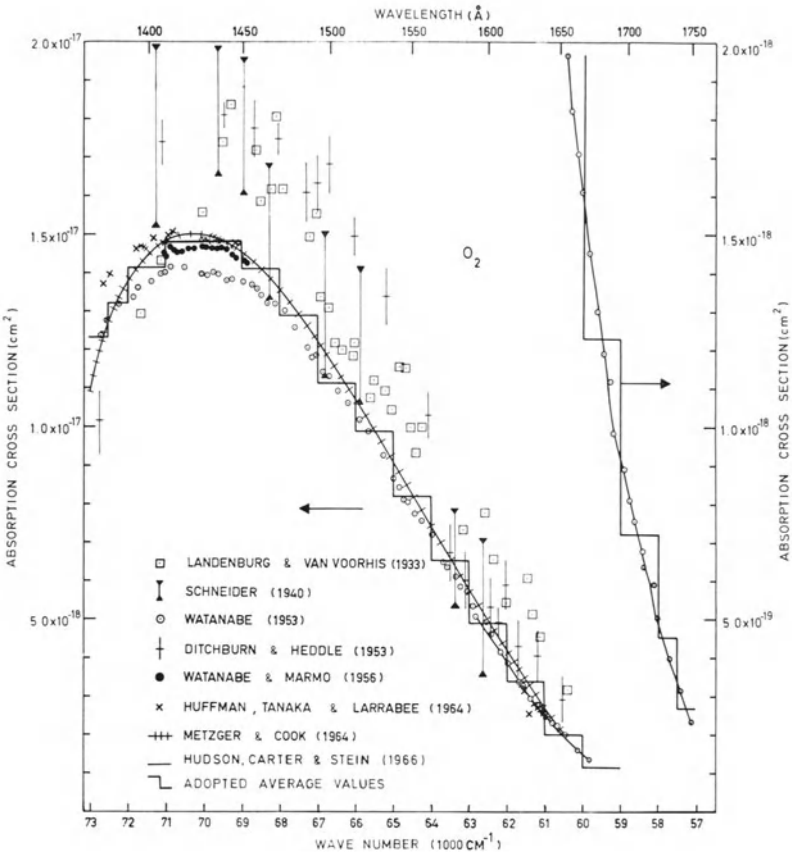

Fig. 3. Absorption cross section of molecular oxygen vs wavelength and versus wavenumber in the Schumann continuum.

ments of absorption properties by Ackerman *et al.* (1969), and of the structure of the bands by Ackerman and Biaumé (1970), have led to a detailed evaluation of the absorption cross section taking temperature effects into account (Ackerman *et al.*, 1970). Applications of these new data are presented by Kockarts (1971), this volume, p. 160.

Above 2000 Å the Herzberg continuum extends up to 2439 Å. Its absorption cross section ranges from about 10^{-23} to 10^{-24} cm^2. Such low values imply that in this wavelength region, molecular oxygen influences the atmospheric transparency only in the stratosphere at heights around 25 km. In fact the strong absorption of ozone limits the role of oxygen to the narrow optical window of 2000 Å which is essential in the process of stratospheric ozone formation.

4. Solar Flux

From the first spectroscopic measurements of the solar ultraviolet radiation the conclusion was drawn that the considerable intensity decay taking place at 3000 Å towards shorter wavelengths was due to solar absorption itself. This phenomenon was attributed to the absorption by ozone after the presence of this atmospheric constituent was firmly established by Fowler and Lord Rayleigh in 1917, and after ground-based study of its absorption of the solar radiation at various zenith distances was performed by Fabry and Buisson in 1921.

At shorter wavelengths, rocket-borne experiments have brought information on the solar ultraviolet radiation since 1946. These data have already been reviewed several times (Hinteregger, 1965). In the wavelength range here considered the available values of solar radiation intensities were until recently those published in 1961 by Detwiler *et al.* (1961). In the range from 2000 Å to 1400 Å, these authors believed that the accuracy of their data was better than $\pm 20\%$ and were fairly sure that there were no errors greater than a factor of 1.5, whereas below 1300 Å errors as great as a factor of two or more were possible.

Using also photographic detection, Bonnet (1968) has obtained values of the solar flux from about 2000 Å to 3000 Å by integrating the flux measured at different locations of the solar disk using a rocket-borne instrument. His data indicated a much more important discontinuity, centered at 2085 Å, than had been previously measured. However, his values were practically in agreement with the previous ones outside of the discontinuity.

In 1968 also, Ackerman *et al.* (1968) reported observations made during the first flight of a balloon-borne photoelectric monochromator viewing the whole solar disk which indicated an even larger amplitude for the discontinuity. Their results showed also that the solar ultraviolet intensity below 2000 Å had been previously overestimated. This has since been confirmed by subsequent flights which are described elsewhere, one of them being discussed in detail by Frimout (1969).

Measurements in the solar spectrum between 1400 and 1875 Å with a photoelectric rocket-borne spectrometer have been published in 1969 by Parkinson and Reeves (1969) and correspond to a solar black body temperature of the order of 4500 K or less, namely much lower than the earlier values given by Detwiler *et al.* (1961).

This year finally, Widing *et al.* (1970), analysing rocket spectra photographed in 1966, have deduced new flux values which are situated as shown in Figure 4, between the two extremes. They are in agreement with the data of Ackerman *et al.* (1968) at 1950 Å.

5. Discussion and Conclusion

The solar ultraviolet of interest to the mesosphere may now be defined more easily. It appears to cover the whole wavelength interval that we have examined after excluding the range covered by the Schumann continuum. Below this feature, considering the absolute intensity, only the Lyman α line plays an important role. Since the sun is radiating more and more strongly towards longer wavelengths above 1200 Å, the solar photons have an increasingly important effect in the mesosphere. Below 2000 Å, the radiation has very much the character of a continuum, while above, it presents a

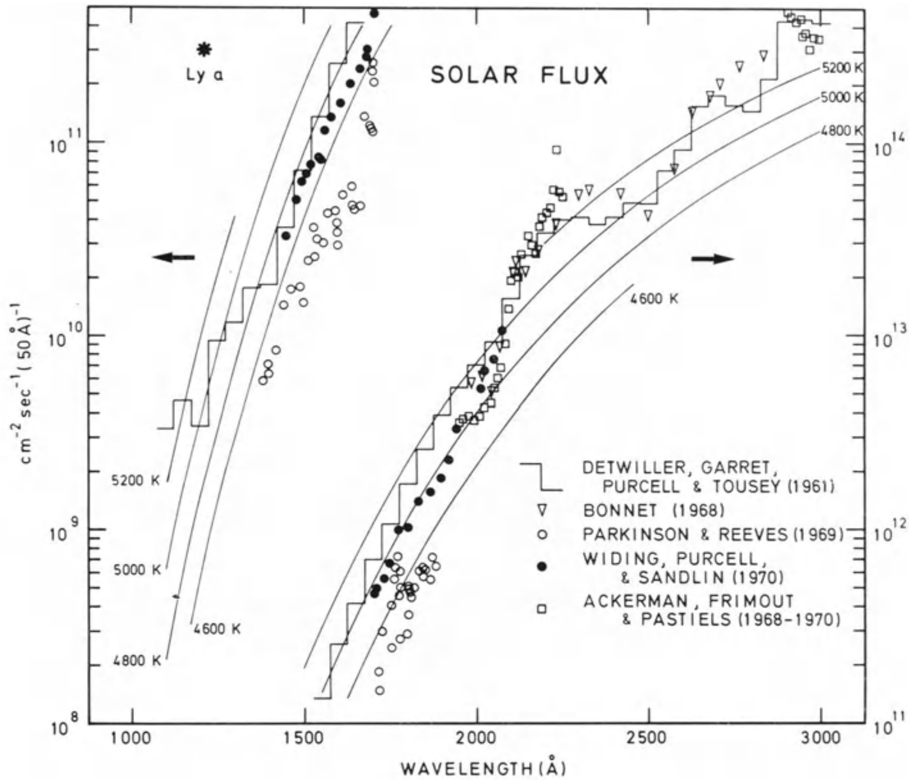

Fig. 4. Flux of solar photons at one AU vs wavelength from 1000 Å to 3000 Å.

very complicated structure. In some applications intensity data at high resolution would be very useful.

Until two or three years ago the situation was rather comfortable from the aeronomical point of view since only one set of data existed. All authors referred to the work of Detwiler *et al.* (1961). New data have since been obtained showing that these authors were a little too optimistic about the accuracy of their measurements. The new values necessarily imply making a choice. This choice has to be precisely specified to allow comparison of the results obtained in photochemical evaluations, for instance. One set of adopted values is presented in Table I with values of absorption cross sections of O_2 and O_3. The adopted solar ultraviolet flux is based on the data given by Detwiler *et al.* (1961) from 1163 to 1428 Å, by Widing *et al.* (1970) from 1423 Å to 1942 Å, by Ackerman *et al.* (1968) and by Frimout (1969) from 1942 Å to 2299 Å, by Detwiler *et al.* (1961) and by Tousey (1963) from 2299 Å to 3625 Å, and by Johnson (1954) at longer wavelength. This is of course not a final choice and new data are now required.

The question of variability with time arises more strongly than ever. The dispersion of the experimental results shows at least that experimental techniques have to be

TABLE I

Flux of solar photons, q, at one AU, absorption cross section of O_2 and of O_3, $\sigma(O_2)$ and $\sigma(O_3)$, for wavelength intervals $\Delta\lambda$ and wavenumber intervals $\Delta\nu$ from Ly-α to 7300 Å

No.	$\Delta\lambda$(Å)	$\Delta\nu$(cm^{-1})	q(cm^{-2} s^{-1})	$\sigma(O_2)$ (cm^2)	$\sigma(O_3)$ (cm^2)
1	Ly α 1.215,67	82.259	3.00×10^{11}	1.00×10^{-20}	2.32×10^{-17}
2	1.170–1.163	85.500–86.000	1.03×10^{8}	2.00×10^{-20}	7.80×10^{-18}
3	1.176–1.170	85.000–85.500	2.66	1.25×10^{-18}	7.97
4	1.183–1.176	84.500–85.000	1.12	2.55×10^{-19}	8.66
5	1.190–1.183	84.000–84.500	1.24	3.00×10^{-20}	9.51
6	1.198–1.190	83.500–84.000	1.82	3.75×10^{-19}	1.25×10^{-17}
7	1.205–1.198	83.000–83.500	1.90	4.45×10^{-18}	1.84
8	1.212–1.205	82.500–83.000	7.40	8.35	2.19
9	1.220–1.212	82.000–82.500	2.28×10^{9}	6.00×10^{-19}	2.30
10	1.227–1.220	81.500–82.000	3.67	2.35	2.26
11	1.235–1.227	81.000–81.500	1.36	4.50	2.06
12	1.242–1.235	80.500–81.000	1.61	3.35	1.30
13	1.250–1.242	80.000–80.500	1.32	1.75×10^{-17}	8.91×10^{-18}
14	1.258–1.250	79.500–80.000	1.41	8.95×10^{-19}	7.24
15	1.266–1.258	79.000–79.500	3.11	4.30	6.09
16	1.274–1.266	78.500–79.000	1.06	1.10	5.66
17	1.282–1.274	78.000–78.500	1.37	2.05	5.87
18	1.290–1.282	77.500–78.000	1.02	4.43	6.47
19	1.299–1.290	77.000–77.500	1.14	5.55	8.14
20	1.307–1.299	76.500–77.000	7.29	4.20	1.24×10^{-17}
21	1.316–1.307	76.000–76.500	2.20	6.85	1.52
22	1.324–1.316	75.500–76.000	1.59	1.45×10^{-18}	1.47
23	1.333–1.324	75.000–75.500	2.21	2.25	1.51
24	1.342–1.333	74.500–75.000	1.24×10^{10}	2.30×10^{-18}	1.51×10^{-17}
25	1.351–1.342	74.000–74.500	1.99×10^{9}	4.55	1.65
26	1.360–1.351	73.500–74.000	3.09	7.23	1.54
27	1.370–1.360	73.000–73.500	2.57	9.50	1.35
28	1.379–1.370	72.500–73.000	2.74	1.23×10^{-17}	1.05
29	1.389–1.379	72.000–72.500	3.10	1.32	7.97×10^{-18}
30	1.408–1.389	71.000–72.000	7.60	1.36	7.17
31	1.428–1.408	70.000–71.000	1.01×10^{10}	1.40	6.28
32	1.449–1.428	69.000–70.000	1.30	1.48	5.66
33	1.470–1.449	68.000–69.000	1.82	1.41	5.23
34	1.492–1.470	67.000–68.000	2.33	1.29	4.47
35	1.515–1.492	66.000–67.000	2.66	1.15	3.69
36	1.538–1.515	65.000–66.000	2.90	9.91×10^{-18}	2.93
37	1.562–1.538	64.000–65.000	3.60	8.24	2.19
38	1.587–1.562	63.000–64.000	4.75	6.58	1.63
39	1.613–1.587	62.000–63.000	6.40	4.97	1.20
40	1.639–1.613	61.000–62.000	5.49	3.45	9.77×10^{-19}
41	1.667–1.639	60.000–61.000	1.19×10^{11}	2.08	8.66
42	1.695–1.667	59.000–60.000	1.76	1.23	8.14
43	1.724–1.695	58.000–59.000	2.32	7.22×10^{-19}	8.17
44	1.739–1.724	57.500–58.000	1.44	4.58	8.57
45	1.754–1.739	57.000–57.500	1.83	2.74	8.40
46	1.770–1.754	56.500–57.000	2.34	[a]	8.11
47	1.786–1.770	56.000–56.500	2.62	[a]	7.99
48	1.802–1.786	55.500–56.000	2.88×10^{11}	[a]	7.86×10^{-19}
49	1.818–1.802	55.000–55.500	3.14	[a]	7.63

[a] See Ackerman *et al.* (1970).

Table I (Continued)

No.	$\Delta\lambda$(Å)	$\Delta\nu$(cm^{-1})	q(cm^{-2} s^{-1})	$\sigma(O_2)$ (cm^2)	$\sigma(O_3)$ (cm^2)
50	1.835–1.818	54.500–55.000	3.81×10^{11}	[a]	7.29×10^{-19}
51	1.852–1.835	54.000–54.500	4.43	[a]	6.88
52	1.869–1.852	53.500–54.000	4.95	[a]	6.40
53	1.887–1.869	53.000–53.500	5.94	[a]	5.88
54	1.905–1.887	52.500–53.000	6.59	[a]	5.31
55	1.923–1.905	52.000–52.500	7.26	[a]	4.80
56	1.942–1.923	51.500–52.000	9.85	[a]	4.38
57	1.961–1.942	51.000–51.500	1.27×10^{12}	[a]	4.11
58	1.980–1.961	50.500–51.000	1.39	[a]	3.69
59	2.000–1.980	50.000–50.500	1.53	[a]	3.30
60	2.020–2.000	49.500–50.000	1.60	[a]	3.26
61	2.041–2.020	49.000–49.500	1.74	1.14×10^{-23}	3.26
62	2.062–2.041	48.500–49.000	2.31	1.05	3.51
63	2.083–2.062	48.000–48.500	4.20	1.00	4.11
64	2.105–2.083	47.500–48.000	7.30	9.55×10^{-24}	4.84
65	2.128–2.105	47.000–47.500	9.42	8.93	6.26
66	2.150–2.128	46.500–47.000	1.06×10^{13}	8.28	8.57
67	2.174–2.150	46.000–46.500	1.34	7.60	1.17×10^{-18}
68	2.198–2.174	45.500–46.000	1.32	6.92	1.52
69	2.222–2.198	45.000–45.500	1.73	6.28	1.97
70	2.247–2.222	44.500–45.000	1.80	5.65	2.55
71	2.273–2.247	44.000–44.500	1.82	5.03	3.24
72	2.299–2.273	43.500–44.000	2.26	4.40	4.00
73	2.326–2.299	43.000–43.500	2.40	3.76	4.83
74	2.353–2.326	42.500–43.000	2.25	3.09	5.79
75	2.381–2.353	42.000–42.500	2.21	2.44	6.86
76	2.410–2.381	41.500–42.000	2.32	1.75	7.97
77	2.439–2.410	41.000–41.500	2.50	6.74×10^{-25}	9.00
78	2.469–2.439	40.500–41.000	2.73		1.00×10^{-17}
79	2.500–2.469	40.000–40.500	2.88		1.07
80	2.532–2.500	39.500–40.000	3.02		1.11
81	2.564–2.532	39.000–39.500	3.97		1.12
82	2.597–2.564	38.500–39.000	7.13		1.11
83	2.632–2.597	38.000–38.500	4.37		1.03
84	2.667–2.632	37.500–38.000	1.12×10^{14}		9.43×10^{-18}
85	2.703–2.667	37.000–37.500	1.25		8.23
86	2.740–2.703	36.500–37.000	1.16		6.81
87	2.778–2.740	36.000–36.500	1.19		5.31
88	2.817–2.778	35.500–36.000	1.38		3.99
89	2.857–2.817	35.000–35.500	1.70		2.84
90	2.899–2.857	34.500–35.000	2.46		1.92
91	2.941–2.899	34.000–34.500	3.90		1.14
92	2.985–2.941	33.500–34.000	3.99		6.60×10^{-19}
93	3.030–2.985	33.000–33.500	3.86		3.69
94	3.077–3.030	32.500–33.000	5.08		1.97
95	3.100 ($\pm$ 25)	32.520–32.000	5.92		1.05
96	3.150	32.000–31.496	6.05		5.23×10^{-20}
97	3.200	31.496–31.008	6.94		2.91
98	3.250	31.008–30.534	8.12		1.50
99	3.300	30.534–30.075	9.71		7.78×10^{-21}
100	3.350	30.075–29.630	8.97		3.72

[a] See Ackerman *et al.* (1970).

Table I (Continued)

No.	$\Delta\lambda$(Å)	$\Delta\nu$(cm^{-1})	q(cm^{-2} s^{-1})	$\sigma(O_2)$ (cm^2)	$\sigma(O_3)$ (cm^2)
101	3.400 ($\pm$25)	29.630–29.197	9.44×10^{14}		1.71×10^{-21}
102	3.450	29.197–28.777	1.01×10^{15}		7.46×10^{-22}
103	3.500	28.777–28.369	1.03		2.66
104	3.550	28.369–27.972	1.03		1.09
105	3.600	27.972–27.586	1.04		5.49×10^{-23}
106	3.650	27.586–27.211	1.18		–
107	3.700	27.211–26.846	1.23		–
108	3.750	26.846–26.490	1.24		–
109	3.800	26.490–26.144	1.17		–
110	3.850	26.144–25.806	1.11		–
111	3.900	25.806–25.478	1.09		–
112	3.950	25.478–25.157	1.19		–
113	4.000	25.157–24.845	1.54		–
114	4.050	24.845–24.540	1.90		–
115	4.100	24.540–24.242	1.99		2.91
116	4.150	24.242–23.952	1.99		3.14
117	4.200	23.952–23.669	2.02		3.99
118	4.250	23.669–23.392	2.01		6.54
119	4.300	23.392–23.121	1.94		6.83
120	4.350	23.121–22.851	1.98		8.66
121	4.400	22.851–22.599	2.25		1.25×10^{-22}
122	4.450	22.599–22.346	2.39		1.49
123	4.500	22.346–22.099	2.48		1.71
124	4.550	22.099–21.858	2.49		2.12
125	4.600	21.858–21.622	2.48		3.57
126	4.650	21.622–21.390	2.50		3.68
127	4.700	21.390–21.164	2.55		4.06
128	4.750	21.164–20.942	2.61		4.89
129	4.800	20.942–20.725	2.59		7.11
130	4.850	20.725–20.513	2.46		8.43
131	4.900	20.513–20.504	2.44		8.28
132	4.950	20.504–20.100	2.53		9.09
133	5.000	20.100–19.900	2.48		1.22×10^{-21}
134	5.050	19.900–19.704	2.49		1.62
135	5.100	19.704–19.512	2.50		1.58
136	5.150	19.512–19.324	2.43		1.60
137	5.200	19.324–19.139	2.43		1.78
138	5.250	19.139–18.957	2.52		2.07
139	5.300	18.957–18.779	2.58		2.55
140	5.350	18.779–18.605	2.64		2.74
141	5.400	18.605–18.433	2.67		2.88
142	5.450	18.433–18.265	2.70		3.07
143	5.500	18.265–18.100	2.68		3.17
144	5.550	18.100–17.937	2.66		3.36
145	5.600	17.937–17.778	2.66		3.88
146	5.650	17.778–17.621	2.67		4.31
147	5.700	17.621–17.467	2.67		4.67
148	5.750	17.467–17.316	2.69		4.75
149	5.800	17.316–17.667	2.71		4.55
150	5.850	17.667–17.021	2.71		4.35
151	5.900	17.021–16.878	2.71		4.42
152	5.950	16.878–16.736	2.72		4.61

Table I (Continued)

No.	$\Delta\lambda$(Å)	$\Delta\nu$(cm^{-1})	q(cm^{-2} s^{-1})	$\sigma(O_2)$ (cm^2)	$\sigma(O_3)$ (cm^2)
153	6.000 (± 25)	16.736–16.598	2.72×10^{15}		4.89×10^{-21}
154	6.050	16.598–16.461	2.71		4.84
155	6.100	16.461–16.326	2.70		4.54
156	6.150	16.326–16.194	2.70		4.24
157	6.200	16.194–16.064	2.70		3.90
158	6.250	16.064–15.936	2.69		3.60
159	6.300	15.936–15.810	2.68		3.43
160	6.350	15.810–15.686	2.67		3.17
161	6.400	15.686–15.564	2.66		2.74
162	6.450	15.564–15.444	2.65		2.61
163	6.500 (± 50)	15.384–15.265	3.95		2.40
164	6.600	15.265–15.038	5.22		2.07
165	6.700	15.038–14.815	5.18		1.72
166	6.800	14.815–14.598	5.14		1.37
167	6.900	14.598–14.388	5.09		1.11
168	7.000	14.388–14.184	5.04		9.13×10^{-22}
169	7.100	14.184–13.986	4.99		7.93
170	7.200	13.986–13.793	4.94		6.40
171	7.300	13.793–13.605	4.90		5.14

considerably improved before an answer can be given. For Lyman α, a rather important variability may be taken as certain.

Finally, if ozone and oxygen have up to now been considered as the absorbers of the ultraviolet radiation related to the mesosphere, one has still to be cautious since other absorbers might be involved. Indications of such effects have been recently given in the 1300 Å region by Reid and Withbroe (1970) and in the 2000 Å region by Ackerman *et al.* (1968).

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