Planet. Space Sci. Vol. 28, pp. 85–103. Pergamon Press Ltd., 1980. Printed in Northern Ireland.

ATMOSPHERIC ABSORPTION IN THE O_2 SCHUMANN–RUNGE BAND SPECTRAL RANGE AND PHOTODISSOCIATION RATES IN THE STRATOSPHERE AND MESOPHERE

MARCEL NICOLET
Institut Royal Météorologique, 3, Avenue Circulaire, 1180 Brussels, Belguim

and

WILLIAM PEETERMANS
Institut d'Aéronomie Spatiale

(*Received* 30 *August* 1979)

Abstract—A general analysis of the absorption of the Schumann–Runge bands of molecular oxygen has been made in order to compare the various experimental and theoretical results which have been obtained for an application to the O_2 atmospheric absorption and its photodissociation in the mesosphere and stratosphere. The different values of the oscillator strengths deduced from the laboratory absorption spectra and of the predissociation linewidths used for the calculation of the absorption have been compared.

Calculations based on a Voight profile of the O_2 rotational lines have led to simple formulas for atmospheric applications taking into account that the total photodissociation rate in the stratosphere depends strongly on the absorption of solar radiation in the spectral range of the O_2 Herzberg continuum. Specific examples are given.

1. INTRODUCTION

The solar u.v. radiation between 200 and 170 nm is absorbed by the Schumann–Runge bands of molecular oxygen in the mesosphere and stratosphere. The first experimental results on the O_2 absorption cross-section of the Schumann–Runge rotational lines obtained by Hudson and Carter (1968), Hudson *et al.* (1969), Hudson and Carter (1969), Ackerman *et al.* (1969), Ackerman and Biaumé (1970) and Biaumé (1972a, b) have been the basis for an application to atmospheric problems (Hudson *et al.*, 1969; Kockarts, 1971, 1976; Hudson and Mahle, 1972; Fang *et al.*, 1974; Park, 1974; Muramatsu, 1975; Nicolet and Peetermans, 1976 unpublished; Shimazaki *et al.*, 1977; Logan *et al.*, 1978; Blake, 1979; Cann *et al.*, 1979).

More recent analyses of experimental parameters (Huebner *et al.* 1975; Lewis *et al.*, 1978, 1979 to be published; Frederick and Hudson, 1979) illustrate the difficulty of obtaining accurate values of the most important spectroscopic parameters.

The molecular constants (Table 1) for the O_2 Schumann–Runge bands as used by Fang *et al.* (1974), come from experimental data obtained by Ackerman and Biaumé (1970) and by Brix and Herzberg (1954) and analysed for the fine structure of the upper level $^3\Sigma_{v'>q}$ by Bergeman and Wofsy (1972) and are generally accepted. If certain numerical values of the oscillator strengths are of the same order of magnitude [Tables 2(a) and (b)], there are still differences which may lead to discrepancies in the determination of the absolute value of the atmospheric optical depth in the spectral range of some bands. For several bands, it is not easy to find an accurate mean value of the oscillator strength. The differences in the values of the oscillator strengths, used even in recent publications, exemplify the difficulties of a correct choice for atmospheric applications in all circumstances: thus the differences between the recent values of Frederick and Hudson (1979) and Lewis *et al.* (to be published) are +23%, −23%, +15% and −4% for the (2–0), (3–0), (4–0) and (5–0) bands respectively. It must be emphasized that an exact knowledge of the linewidths is required for a precise calculation where the atmospheric optical depth is much above unity. The experimental and theoretical results which are given in Table 3 and illustrated in Fig. 1 also show serious differences for certain Schumann–Runge bands. Even if it is accepted that the photographic method overestimates the linewidths, it is not always possible to understand discrepancies between the other results. For instance, the values obtained by Frederick and Hudson (1979) and by Lewis *et al.* (1979) for the (2–0), (3–0), (4–0) and (5–0) bands lead to the average ratios 0.4, 1.5, 1.4 and 1.2, respectively,

TABLE 1. CONSTANTS FOR O_2 SCHUMANN–RUNGE BANDS

	v	B_v	D_v	λ_v	γ_v	T_e
$X^3\Sigma_g^+$	0	1.43768	4.913×10^{-6}	1.9848	−0.00843	
	1	1.42198	4.825	1.9848	−0.00843	
$B^3\Sigma_u^-$	v'					
	0	0.8127	5.06×10^{-6}	1.63	−0.007	49358.2
	1	0.8001	6.61	1.49	−0.008	50045.7
	2	0.7852	5.10	1.45	−0.009	50710.8
	3	0.7699	4.54	1.50	−0.010	51352.3
	4	0.7537	3.56	1.50	−0.010	51969.8
	5	0.7372	5.71	1.50	−0.011	52561.4
	6	0.7194	5.71	1.50	−0.012	53122.8
	7	0.6997	6.96	1.50	−0.014	53656.3
	8	0.6771	6.71	1.50	−0.015	54156.3
	9	0.6531	8.60	1.63	−0.022	54622.3
	10	0.6279	1.26×10^{-5}	1.60	−0.028	55050.9
	11	0.5990	2.14	1.81	−0.050	55438.9
	12	0.5621	1.29	2.15	−0.060	55784.5
	13	0.5244	1.67	2.54	−0.094	56085.2
	14	0.4832	2.09	2.83	−0.137	56339.9
	15	0.4396	2.64	3.36	−0.179	56549.7
	16	0.3945	3.3	4.04	−0.272	56718.1
	17	0.3471	4.0	5.18	−0.349	56850.2
	18	0.2872	5.5	6.51	−0.494	56951.6
	19	0.2649	6.0	7.63	−0.604	57025.8

TABLE 2(a). ABSORPTION OSCILLATOR STRENGTHS FOR THE O_2 SCHUMANN–RUNGE BANDS

Band	0–0	1–0	2–0	3–0	4–0	5–0
Author						
Bethke (1959)			2.3×10^{-8}	7.4×10^{-8}	2.74×10^{-7}	7.28×10^{-7}
Halmann (1966)			2.6×10^{-8}	8.2×10^{-8}	2.4×10^{-7}	7.48×10^{-7}
Farmer *et al.* (1968)			2.69×10^{-8}	1.54×10^{-7}	7.11×10^{-7}	2.80×10^{-6}
Ackerman *et al.* (1970)	3.45×10^{-10}	3.9×10^{-9}	2.38×10^{-8}	9.9×10^{-8}	3.21×10^{-7}	8.52×10^{-7}
Hasson *et al.* (1970)	3.3×10^{-10}	3.5×10^{-9}	1.99×10^{-8}	6.8×10^{-8}		
Allison *et al.* (1971)	2.77×10^{-10}	3.31×10^{-9}	2.03×10^{-8}	8.62×10^{-8}	2.86×10^{-7}	7.87×10^{-7}
Hudson and Mahle (1972)	2.62×10^{-10}	3.05×10^{-9}	2.7×10^{-8}	7.1×10^{-8}	2.5×10^{-7}	6.1×10^{-7}
Huebner *et al.* (1975)		2.7×10^{-9}	6.2×10^{-8}	5.6×10^{-8}	2.87×10^{-7}	7.39×10^{-7}
Frederick and Hudson (1979)			2.77×10^{-8}	7.51×10^{-8}	3.04×10^{-7}	7.39×10^{-7}
Lewis *et al.* (1979)			2.36×10^{-8}	9.70×10^{-8}	2.65×10^{-7}	7.70×10^{-7}

TABLE 2(b). COMPARISON BETWEEN MEAN BAND OSCILLATOR STRENGTHS ($\times10^5$) OBTAINED BY VARIOUS AUTHORS. O_2 SCHUMANN–RUNGE BANDS. FROM $v''=0$

v'	Bethke (1959)	Farmer *et al.* (1968)	Ackerman *et al.* (1970)	Allison *et al.* (1971)	Hudson and Mahle (1972)	Huebner *et al.* (1975)	Lewis *et al.* (1978)	Frederick and Hudson (1979)	Blake (1979)
6	0.173	0.44	0.91	0.185	0.17	0.170	0.174±0.003	0.162±0.004	0.218
7	0.356	0.815	0.381	0.375	0.35	0.350	0.373±0.007	0.315±0.008	0.444
8	0.675	1.22	0.668	0.671	0.60	0.685	0.732±0.015	0.578±0.004	0.807
9	1.07	1.50	1.06	1.077	1.0	1.05	1.28±0.04	1.04±0.40 −0.20	1.30
10	1.56	2.05	1.57	1.580	1.6	1.60	1.77±0.03	2.60+0.47 −0.20	1.92
11	2.16	2.74	2.09	2.137	1.7	2.26	2.50±0.05	1.80+0.53 −0.08	2.57
12	2.81	3.58	2.53	2.668	2.5	2.88	3.13±0.07	2.09±0.08	3.16
13	3.17	3.66	2.88	3.070	4.5	3.41	3.48±0.10	2.69+0.36 +0.20	3.58
14	3.24	3.69	3.03	3.254	5.0	3.77	4.22±0.10		3.74

TABLE 3. O_2 SCHUMANN–RUNGE BANDS. PREDISSOCIATION WIDTHS (cm^{-1})

v'	Ackerman and Biaume (1970)	Hudson and Mahle (1972)	Julienne (1976)	Lewis Carver *et al.* (1978)	Frederick and Hudson (1979)	Blake (1979)
0	1.0±0.1	(0.001)	0.06			0.1
1	1.2±0.2	(0.002)	0.45			1.0
2	1.2±0.2	0.34±15	0.27	0.62±0.08	0.24±0.2	0.25
3	2.1±0.2	1.25±0.35	1.30	1.2±0.1	1.84±0.08	1.2
4	3.7±0.2	3.30±0.20	2.93	3.0±0.4	4.18±0.09	3.0
5	2.5±0.2	2.20±0.20	1.33	1.9±0.3	2.3±0.5	1.75
6	1.9±0.2	1.70±0.10	1.80	1.43±0.07	1.1±0.2	1.6
7	2.2±0.2	2.25±0.05	1.90	1.63±0.11	1.70±0.13	1.0
8	2.1±0.2	2.21±0.20	1.59	1.35±0.08	1.43±0.16	1.2
9	1.1±0.1	0.72±0.08	0.89	0.67±0.04	0.76±0.4	0.7
10	1.7±0.1	0.34±0.05	0.67	0.69±0.05	0.42±0.7	0.5
11	2.0±0.1	1.80±0.12	1.30	0.98±0.06	1.3±0.4	0.9
12	1.0±0.1	0.48±0.05	0.70	0.60±0.02	0.81±0.06	0.5
13	0.6±0.1	0.08±0.05	0.20	0.14±0.01	0.13±0.01	0.15
14	0.5±0.1	0.06±0.05	0.20	0.08±0.01		0.1
15	0.6±0.1	0.20±0.05	0.29			0.1
16		0.25±0.05	0.29			0.2
17		(0.4)				0.4
18		(0.4)				0.4
19		(0.4)				0.4

i.e. to differences which are too great. It is therefore necessary to apply the experimental results in their present form for an atmospheric study and to try to determine the importance of possible errors in the calculation of the various total photodissociation rates.

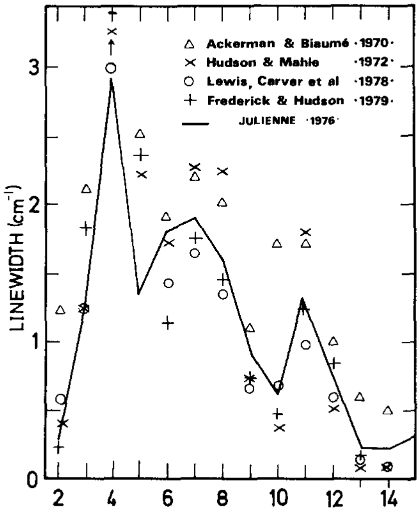

FIG. 1. LINEWIDTHS (cm^{-1}) OF SCHUMANN–RUNGE BANDS OF MOLECULAR OXYGEN.

Experimental and theoretical values.

2. THE ATMOSPHERIC PROBLEM OF O_2 PHOTODISSOCIATION

If we use current accepted values for the solar flux between 175 and 242 nm, it is possible to determine the photodissociation coefficient J_2 of molecular oxygen with certain values (e.g. Fang *et al.*, 1974) of the oscillator strengths and linewidths of the rotational lines for the O_2 Schumann–Runge bands and mean absorption cross-sections (500 cm^{-1}) for the Herzberg continuum. Final results as given in Fig. 2 show the variation of the ratio of the parts due to the spectral ranges 200–175 nm (Schumann–Runge bands) and 242–175 nm (total spectrum).

The Schumann–Runge band system is of major importance in the mesosphere but contributes only some 10% of the total in the central part of the stratosphere. Consequently, the calculation of the stratospheric J_2 values for molecular oxygen are not very much affected even by errors involved in the determination of the absorption behavior in the Schumann–Runge band system. On the other hand, since the whole mesospheric photochemistry strongly depends on the rotational structure of the Schumann–Runge bands, high precision is required in the determinations of the J_2 value.

In order to test the sensitivity of identical calculations based on different experimental data, we have made a comparison between the numerical

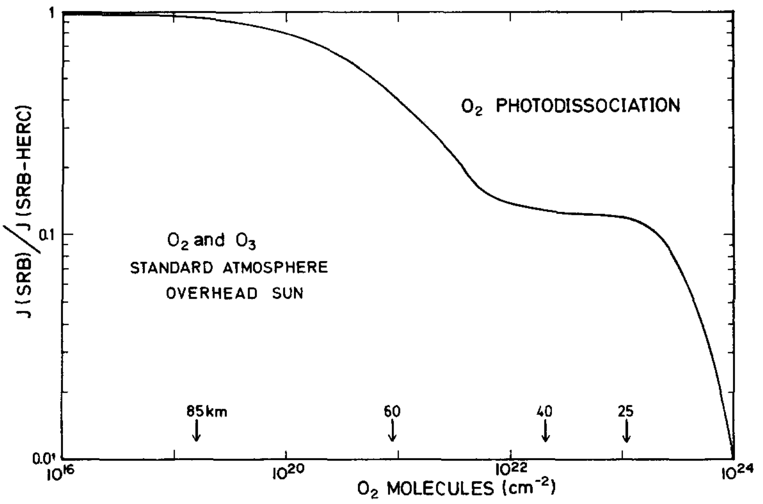

FIG. 2. PHOTODISSOCIATION RATES OF MOLECULAR OXYGEN IN THE MESOSPHERE AND STRATOSPHERE. Ratio of $J_{SRB}(\lambda \leq 200$ nm) to $J_{SRB\text{-}HERC}(\lambda \leq 242$ nm).

results which can be obtained from results obtained by Hudson *et al.* (1969) and by Kockarts (1976).

The parameter

$$R_b(O_2) \equiv \sum_{i=1}^{n} \sigma_i(O_2) \exp[-\sigma_i(O_2)N(O_2)], \quad (1)$$

where $\sigma_i(O_2)$ is the constant absorption (and photodissociation) cross-section (cm^2) for a narrow wavelength interval and $N(O_2)$ is the total number of O_2 absorbing molecules (cm^{-2}) is calculated for each Schumann–Runge band. We can determine

$$J_{2,b} = q_{\infty,b} R_b(O_2), \quad (2)$$

which is the photodissociation coefficient (s^{-1}) if $q_{\infty,b}$ ($cm^{-2}\,s^{-1}$) is the mean solar flux in the spectral range of a Schumann–Runge band at the top of the Earth's atmosphere. The quantity $R_b(O_2)$ allows easy analysis of the photodissociation of molecular oxygen without involving the absolute value of the solar flux. Figure 3 shows examples of the remarkable agreement between the two calculations. The result indicates that laboratory data obtained in 1969–1970 by Hudson *et al.* (1969) and Ackerman *et al.* (1970) are related to methods of analysis which are not too different.

Atmospheric applications of the O_2 absorption effect to other constituents require a different approach. Instead of (1), we must introduce only the effect of the O_2 optical depth. In order to keep the same type of formula for the photodissociation of all constituents, we write for a molecule XY

$$J_{XY} = \sum j_{XY} = \sum q_\infty \sigma_{xy} e^{-\tau(O_2)} e^{-\tau(O_3)}, \quad (3)$$

where q_∞ is the average number of photons ($cm^{-2}\,s^{-1}$) at the top of the Earth's atmosphere for the spectral range which is considered, σ_{XY} is the photodissociation cross-section adapted to such spectral range which can be a mean value for certain constituents but may depend on the temperature and number of molecules (O_2 e.g.) and $\tau(O_2)$ and $\tau(O_3)$ are the optical depths for O_2 and O_3, respectively. The ozone optical depth is related to a mean absorption cross-section $\sigma(O_3)$ which does not play a significant role in the mesosphere because the total number of O_3 molecules is small. The molecular oxygen optical depth involves an absorption cross-section dependent on the temperature and the number of absorbing molecules. Hence, the first problem is the determination of the O_2 absorption behavior which can lead to general mean values of the optical depth. We write for a mean optical depth adapted to a Schumann–Runge band

$$\overline{e^{-\tau(O_2)}} = \frac{1}{n} \sum_{i=1}^{n} \exp[-\tau_i(O_2)] =$$

$$\frac{1}{n} \sum_{i=1}^{n} \exp[-\sigma_i(T)N(O_2)]. \quad (4)$$

This gives mean values $\overline{\tau(O_2)}$ and $\overline{\sigma(O_2)}$ which depend on the temperature and total number of O_2 absorbing molecules. Figure 4 illustrates the variation of $\bar{\tau}$ and $\bar{\sigma}$ with I in $N(O_2)$ for the (5–0) band.

Formula (4) leads to a maximum average value

$$\overline{\sigma_M(T)} = \frac{1}{n} \sum_{i=1}^{n} \sigma_i(T), \quad (5)$$

when $N(O_2) \rightarrow 0$, and to a minimum value

$$\sigma_m(T) = [\sigma_i(T)]_{min}, \quad (6)$$

which corresponds to the smallest value of σ in the adopted spectral range, when $N(O_2) \rightarrow \infty$.

In order to make a comparison between various computations, formula (5) can be used since it gives the average value adopted related to the oscillator strength and to the linewidth. A comparison which is illustrated in Fig. 5 shows the possible differences between various maximum average values of the O_2 absorption cross-sections σ_M at $T = 230$ K. We have deduced these various values corresponding to (5) from data published by Hudson and Mahle (1972), Ackerman *et al.* (1970), Biaumé (1972a, b), Fang *et al.* (1974), Lewis *et al.*, (1978) and our own computations based on a Voight profile with parameters used by Fang *et al.* (1974) and on a Lorentz profile with parameters obtained by Ackerman *et al.* (1970).

Observed differences correspond to differences in experimental parameters (oscillator strength and linewidth) and also in the formulation of the representation of the O_2 optical depth (except for numerical errors in printed tables). It is, therefore, clear that the errors will not decrease with increasing optical depths, but their importance may be limited not only through the compensating effect of positive and negative differences for the various bands but also by a neutralising action due to the effect of other spectral ranges on the total photodissociation rate.

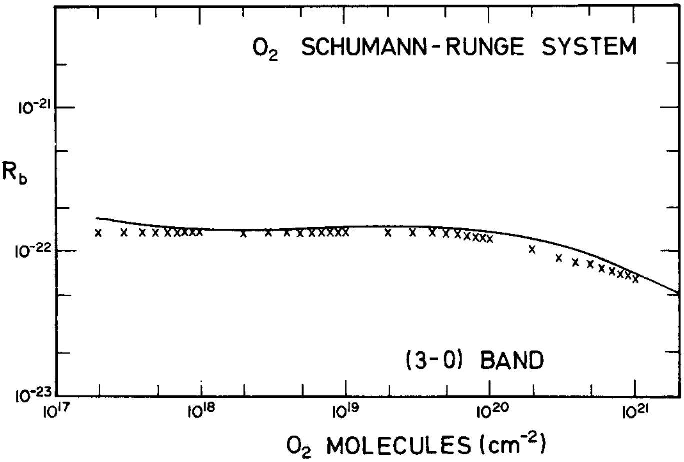

FIG. 3(a). $R_b(O_2)$ FOR THE O_2(3–0) BAND.
See text.—calculated from formula obtained by Kockarts (1976) and × from tables published by Hudson *et al.* (1969).

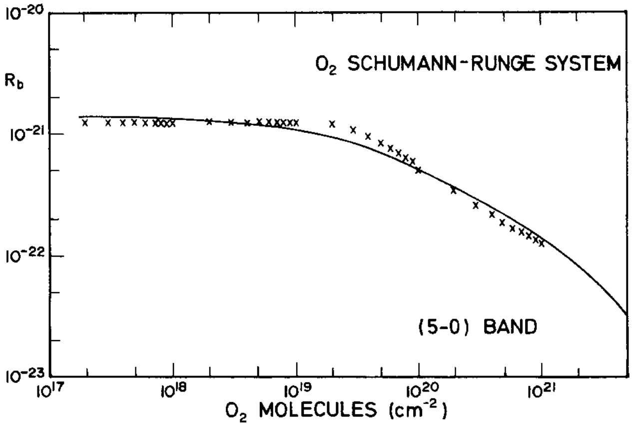

FIG. 3(b). $R_b(O_2)$ FOR THE O_2(5–0) BAND.
See Fig. 3(a).

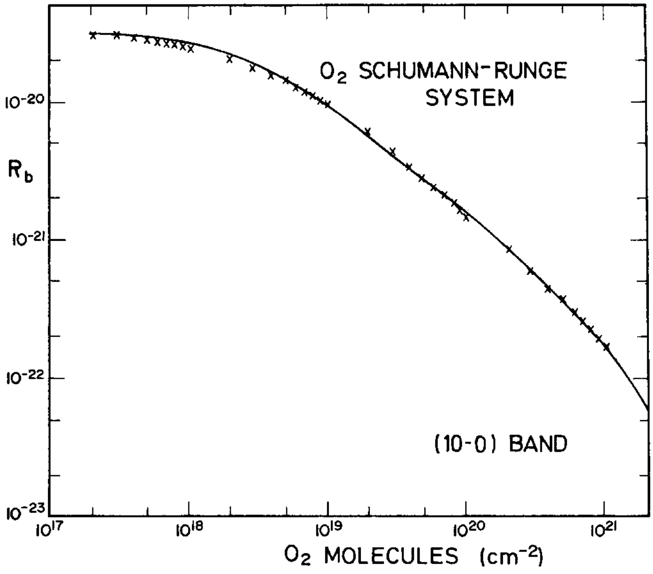

FIG. 3(c). $R_b(O_2)$ FOR THE O_2(10–0) BAND. See Fig. 3(a).

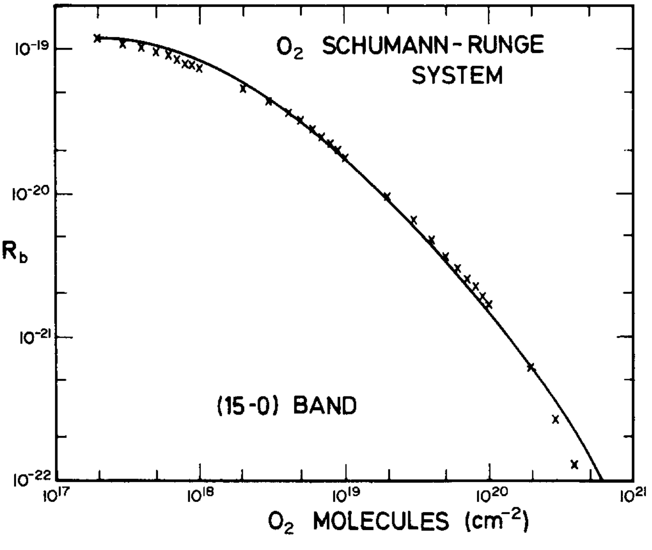

FIG. 3(d). $R_b(O_2)$ FOR THE (15–0) BAND. See Fig. 3(a).

In order to demonstrate how the values of the photodissociation rates J_2, as indicated by their ratios in Fig. 2, are obtained, it is useful to determine what are the respective influences of each Schumann–Runge band compared with the total Schumann–Runge band spectral range (175–200 nm) and also with the total photodissociation rate resulting from the spectral range 242–175 nm which involves the Herzberg continuum. Table 4 gives the various percentages of the photodissociation rates for a few Schumann–Runge bands when they are compared with the 175–200 nm and 175–242 nm spectral range photodissociation coefficients. The principal results are illustrated in Fig. 6 which shows the enhanced effect of bands such as (2–0) when the total number of O_2 molecules is

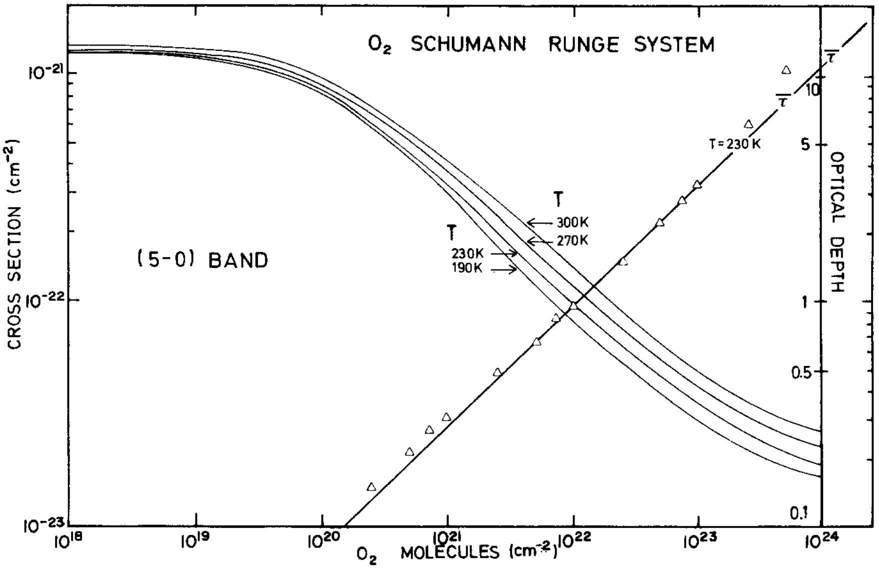

FIG. 4. MEAN ABSORPTION CROSS-SECTION FOR THE (5–0) BAND IN THE O_2 SCHUMANN–RUNGE SYSTEM FOR $T = 190$, 230, 270 AND 300 K WITH THE ASSOCIATED OPTICAL DEPTH AT $T = 230$ K.

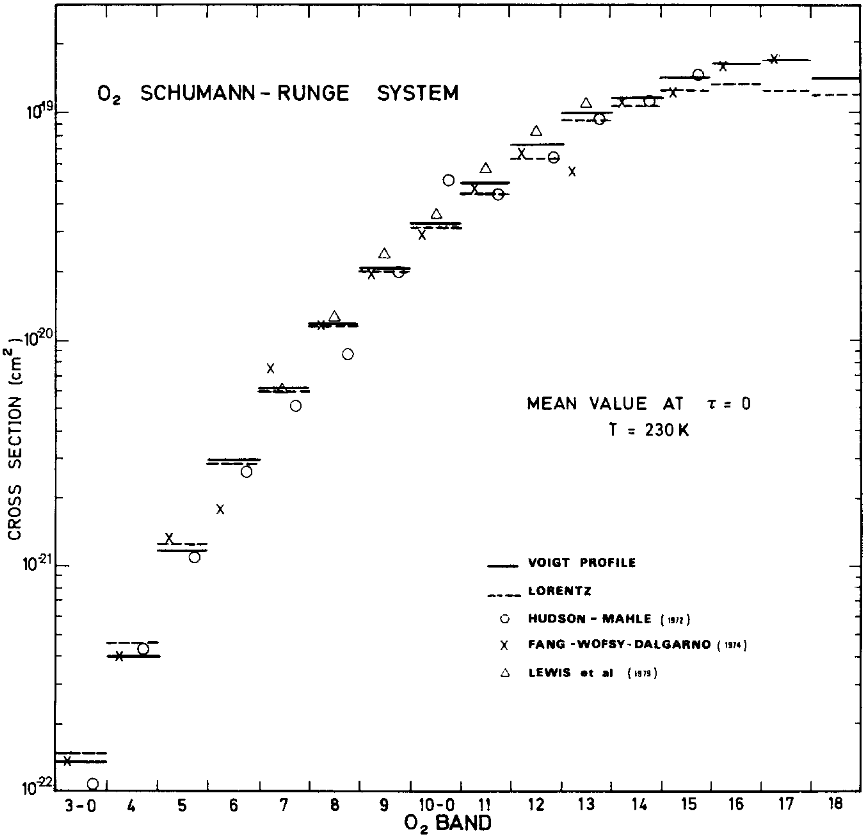

FIG. 5. COMPARISON BETWEEN VARIOUS MEAN VALUES OF THE O_2 ABSORPTION CROSS-SECTIONS IN THE SCHUMANN–RUNGE SYSTEM.

TABLE 4. O_2 PHOTODISSOCIATION RATES. EFFECT OF THE SCHUMANN–RUNGE BAND SYSTEM. TOTAL PERCENTAGE: PERCENTAGE FOR (2–0), (5–0) (10–0) AND (15–0) BANDS FROM 175 TO 200 nm AND FROM 175 TO 242 nm, RESPECTIVELY

$N(O_2)$ (cm^{-2})	$\left[\frac{J(SRB)}{J_{SRB-HERC}}\right]$	Band (2–0)	Band (5–0)	Band (10–0)	Band (15–0)
10^{18}	98	0.1	1.6	9.3	8.7
		0.1	1.6	9.3	8.7
10^{19}	95	0.4	4.5	8.4	5.7
		0.4	4.2	8.0	5.4
10^{20}	79	1.9	10.7	8.4	2.3
		1.5	8.5	6.6	1.8
2.5×10^{20}	66	3.7	12.2	7.9	1.3
		2.5	8.0	5.2	0.8
5×10^{20}	53	5.3	13.0	7.3	0.7
		2.8	6.8	3.8	0.4
10^{21}	39	8.0	13.8	6.4	0.3
		3.1	5.3	2.5	0.1
2.5×10^{21}	23	13.3	14.9	4.8	—
		3.1	3.5	1.1	—
5×10^{21}	16	18.8	15.0	3.1	—
		3.0	2.4	0.3	—
10^{22}	14	26.3	13.9	1.4	—
		3.5	1.9	0.2	—
2.5×10^{22}	12	38.4	10.4	0.2	—
		4.8	1.3	—	—
5×10^{22}	12	48.9	6.9	—	—
		6.0	0.8	—	—
10^{23}	12	59.7	3.6	—	—
		7.2	0.4	—	—
10^{24}	1	86.7	—	—	—
		0.7	—	—	—

increased, i.e. from the upper mesosphere to the stratosphere. The (5–0) band must be considered as the last band belonging to this group, there being a rapid decrease of its importance when $N(O_2) > 5\times10^{22}\ cm^{-2}$. The group of bands near (10–0) relate mainly to the mesosphere. The behavior of the (15–0) band shows that the later bands of the (v'–0) group have their principal effect in the upper mesosphere.

This short analysis indicates clearly that accurate determinations are more important for the bands situated in the 200 nm spectral region than for the bands near 175 nm, particularly for the study of the atmospheric region near the stratopause and the lower mesosphere where photochemical equilibrium conditions can be applied to the O_3 vertical distribution.

In order to determine the importance of numerical differences, a detailed comparison has been made between results based on a Voight profile with parameters used by Fang *et al.* (1974) and with experimental parameters (oscillator strengths and linewidths) determined by Lewis *et al.* (1978). Table 5 gives the results of a comparison of the mean absorption coefficient σ_M for the (6–0)–(14–0) bands at three different temperatures (190, 230 and 270 K). There is good agreement for the (6–0) and (7–0) bands. From (8–0) to (14–0) the positive differences are: +9, +18, +12, +16, +17, +12 and +6%, respectively. Since only the mean value σ_M is

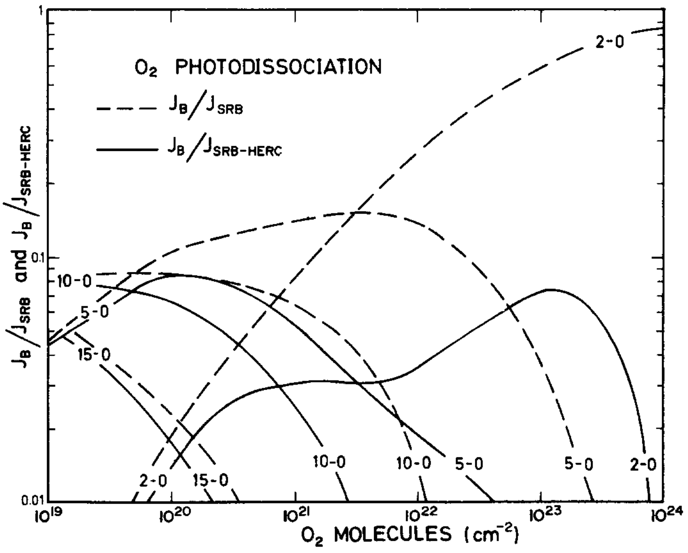

FIG. 6. VARIATION OF THE PHOTODISSOCIATION COEFFICIENT OF A SCHUMANN–RUNGE BAND COMPARED WITH THE TOTAL PHOTODISSOCIATION COEFFICIENT OF THE SCHUMANN–RUNGE BAND SYSTEM AND OF THE HERZBERG CONTINUUM WITH THE SCHUMANN–RUNGE BAND SYSTEM, RESPECTIVELY.

TABLE 5. MEAN ABSORPTION CROSS-SECTION OF O_2 SCHUMANN–RUNGE BANDS: σ_M [FORMULA(5)]

	$T = 190$ K	$T = 230$ K		$T = 270$ K	
14–0	1.23×10^{-19}	1.28×10^{-19}		1.32×10^{-19}	*
	1.40	1.36	+6%	1.31	
13–0	9.60×10^{-20}	9.91×10^{-20}		1.02×10^{-19}	
	1.09×10^{-19}	1.11×10^{-19}	+12%	1.12	
12–0	7.02×10^{-20}	7.14×10^{-20}		7.28×10^{-20}	
	8.22	8.35	+17%	8.49	
11–0	4.83×10^{-20}	4.91×10^{-20}		5.02×10^{-20}	
	5.64	5.74	+16%	5.84	
10–0	3.11×10^{-20}	3.17×10^{-20}		3.24×10^{-20}	
	3.49	3.55	+12%	3.61	
9–0	2.00×10^{-20}	2.02×10^{-20}		2.05×10^{-20}	
	2.37	2.39	+18%	2.41	
8–0	1.15×10^{-20}	1.16×10^{-20}		1.18×10^{-20}	
	1.25	1.27	+9%	1.28	
7–0	5.93×10^{-21}	6.06×10^{-21}		6.18×10^{-21}	
	5.99	6.01		6.07	
6–0	2.83×10^{-21}	2.86×10^{-21}		2.92×10^{-21}	
	2.80	2.83		2.84	

*Parameters deduced from Allison *et al.* (1971).
†Parameters deduced from Lewis *et al.* (1979).

involved, the positive effect is due to the values of the oscillator strengths (Table 2) obtained by Lewis *et al.* (1978) which are greater than the adopted values of Allison *et al.* (1971). The differences in linewidths (Table 3) are responsible for the irregularities in the percentages.

A careful analysis is required for the calculations of the photodissociation rates in the mesosphere. However, the principal bands which play the leading role ($v' \leq 8$) in the stratospheric absorptions related to all photodissociation processes must be studied with the best values which are now available. Clearly the O_2 stratospheric photodissociation coefficients are less affected by systematic errors than the coefficients of constituents for which the total photodissociation rate is almost equally subdivided between the spectral ranges $\lambda < 200$ nm and $\lambda > 200$ nm. In this case, it is necessary to determine for each Schumann–Runge band the differences between the various values of the optical depth $\tau(O_2)$. Figure 7 illustrates such differences. There is perfect agreement for the (7–0)

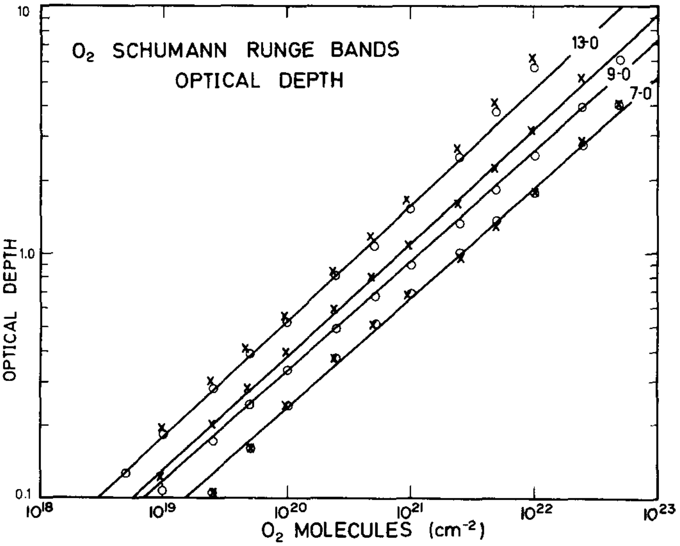

FIG. 7. OPTICAL DEPTHS AT $T = 230$ K DETERMINED FROM LEWIS *et al.* (1978) MEASUREMENTS (X) AND VALUES COMPUTED IN THIS WORK (O).

band, good agreement for the (13–0) band, but an important difference for the (9–0) band which will affect the determination of the solar radiation transmission in the mesosphere.

3. CALCULATION OF J_2

In order to determine J_2 with formula (3), we have first made a complete computation for each Schumann–Runge band by integrating a cross-section with 0.5 cm^{-1} resolution and using a Voight profile at $T = 190$, 230, 270 and 300 K. The detailed results have been analyzed in order to give the mean value of $\overline{\overline{\sigma(O_2)}}$ represented by σ_{XY} in formula (3) and also a different value $\overline{\sigma(O_2)}$ used for the mean optical depth $\tau(O_2)$. With these definitions, we write for each band

$$\overline{\overline{\sigma(O_2)}} = \sum \sigma(O_2)e^{-\tau(O_2)} \Big/ \sum e^{-\tau(O_2)} \qquad (7)$$

and

$$\overline{\sigma(O_2)} = -\frac{1}{N(O_2)} \ln \overline{e^{-\tau(O_2)}}. \qquad (8)$$

An example of the variation of the $\overline{\overline{\sigma(O_2)}}/\overline{\sigma(O_2)}$ ratio is represented in Fig. 8. We can express the variation of $\overline{\overline{\sigma(O_2)}} = \sigma_e(O_2)$ with T and $N(O_2)$ by the following formula:

$$\sigma_e(O_2) = \sigma_m[\sigma_M/\sigma_m]^{1/(1+e^p)}, \qquad (9)$$

where σ_M and σ_m are the maximum and minimum photodissociation cross-sections defined in (5) and (6), respectively; p is an expression given by the polynomial function

$$p = \sum p_i[\ln N(O_2)]^i. \qquad (10)$$

After several trials we have adopted a simple expression with only 2 terms

$$p_2 = p_{2,0} + p_{2,1} \ln N(O_2) \qquad (11)$$

and another expression with six terms

$$p_6 = p_{6,0} + p_{6,1} \ln N(O_2) + \ldots + p_{6,5}[\ln N(O_2)]^5. \qquad (12)$$

Similarly, the transmission related to the mean optical depth $\overline{\tau(O_2)}$ is defined as follows:

$$\exp[-\tau(O_2)] = \exp[-e^{+d}], \qquad (13)$$

where d is given by another polynomial function

$$d = \sum_0^n d_i(\ln N)^i, \qquad (14)$$

leading for $\tau(O_2)$ with two terms to the simple form

$$\ln \tau(O_2) = d_2 \equiv d_{2,0} + d_{2,1} \ln N(O_2) \qquad (15)$$

and with six terms to

$$d_6 = d_{6,0} + d_{6,1} \ln N(O_2) + \ldots + d_{6,5}[\ln N(O_2)]^5. \qquad (16)$$

The computation has been made using the expressions with 2 terms (11) and (15) and those six terms (12) and (16) and comparisons have been made with the detailed calculations. The system of six term function leads to a perfect agreement

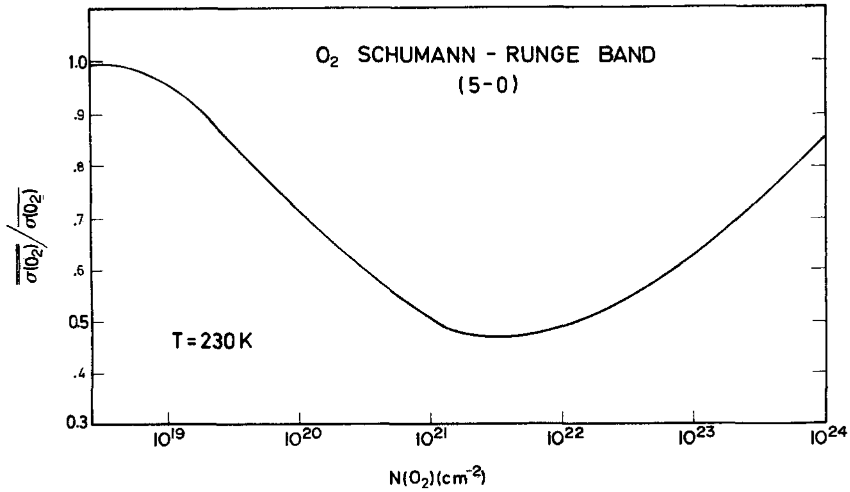

FIG. 8. RATIO OF THE O_2 CROSS-SECTIONS DEFINED BY (7) AND (8) VERSUS THE NUMBER OF MOLECULES (cm^{-2}).

(<1%) with the complete computation while the system with only 2 terms is sufficiently precise for almost all atmospheric purposes. It is not possible to reproduce here all detailed results. However, it is interesting to present (even if there are systematic errors) tables (Table 6) which give the numerical results of the detailed computation the transmission, exp [−optical depth]. These tables show that the temperature effect may be important in certain bands and must be introduced in an atmospheric analysis when high precision is required. However a precise calculation also required at the same time the introduction of the solar zenith angle effect and a transfer from one transmission factor to another depending on the vertical distribution of temperature.

Such detailed computation cannot be used for current application to the mesospheric and stratospheric photochemistry and the use of formulas such as (7)–(16) is needed to simplify the calculation under real atmospheric conditions. The numerical coefficients to be used in formulas (5) with (6), (11) and (15) corresponding to the simplest form are given in Tables 7, 8 and 9, respectively. The photodissociation coefficients $\sigma_M q_\infty$ given in Table 10 correspond to values depending on the temperature where the optical depth is negligible; $\sigma_M q_\infty$ corresponds to the minimum value which can be used in formula (9) which gives the effective photodissociation cross-section depending on the total number of absorbing O_2 molecules.

A comparison has been made for each Schumann–Runge band of the values of $e^{-\tau(O_2)}$ for values of the total number of O_2 molecules, $N(O_2) = 10^{17}$–10^{24} cm^{-2}. The expression with six terms leads to $e^{-\tau(O_2)}$ values reproducing those obtained by the detailed computation with a precision better than ±1%. However, the expression with two terms can be used with sufficient accuracy for all atmospheric purposes if an average temperature of about 230 K is adopted with a limit for the total number of O_2 absorbing molecules $N(O_2) < 5 \times 10^{23}$ cm^{-2} corresponding to the stratospheric region where the solar penetration in the spectral range of the Schumann–Runge band is becoming negligible for photodissociation processes. Table 11 gives a detailed comparison showing how it is possible to fit by simple formulas the variation of the optical depths. Furthermore, the application to the photodissociation rate of molecular oxygen is also possible with the use of formulas (11) and (14). Using solar flux data adopted by Nicolet (1979), the results of a comparison between detailed and simplified calculations are shown in Table 12. The differences cannot be greater than about 10%; the importance of the Herzberg continuum is apparent in the mesosphere (65%), where $N(O_2) = 10^{21}$ cm^{-2}, i.e. at 60 km for an overhead Sun. At $N(O_2) \geq 5 \times 10^{23}$ cm^{-2}, the large errors in the calculation of the Schumann–Runge band photodissociation rate have no importance because they relate to only a fraction of a very small total photodissociation rate.

Another remark must be made in connection

TABLE 6(a). EXP[−OPTICAL DEPTH] (2–0) BAND

$N(O_2)$	190 K	230 K	270 K	300 K
2.5×10^{19}	0.999	0.999	0.999	0.999
5.0	0.998	0.998	0.998	0.998
7.5	0.997	0.997	0.997	0.997
1.0×10^{20}	0.996	0.996	0.996	0.996
2.5	0.991	0.991	0.990	0.990
5.0	0.983	0.987	0.982	0.980
7.5	0.975	0.975	0.974	0.971
1.0×10^{21}	0.869	0.968	0.966	0.963
2.5	0.935	0.933	0.928	0.921
5.0	0.891	0.886	0.878	0.866
7.5	0.853	0.847	0.835	0.818
1.0×10^{22}	0.818	0.811	0.796	0.776
2.5	0.652	0.640	0.614	0.580
5.0	0.457	0.443	0.411	0.374
7.5	0.325	0.310	0.280	0.249
1.0×10^{23}	0.232	0.219	0.193	0.168
2.5	3.19×10^{-2}	2.84×10^{-2}	2.28×10^{-2}	1.8650×10^{-2}
5.0	1.25×10^{-3}	1.03×10^{-3}	7.66×10^{-4}	5.839×10^{-4}
7.5	5.01×10^{-5}	3.96×10^{-5}	2.78×10^{-5}	2.0204×10^{-5}
1.0×1024	2.04×10^{-6}	1.56×10^{-6}	1.05×10^{-16}	7.3447×10^{-7}

TABLE 6(b). EXP [− OPTICAL DEPTH] (7–0) BAND

$N(O_2)$	190 K	230 K	270 K	300 K
1.0×10^{17}	0.999	0.999	0.999	0.999
2.5	0.999	0.999	0.999	0.999
5.0	0.997	0.997	0.997	0.997
7.5	0.996	0.996	0.995	0.995
1.0×10^{18}	0.994	0.994	0.994	0.994
2.5	0.986	0.986	0.985	0.985
5.0	0.974	0.973	0.972	0.971
7.5	0.963	0.961	0.960	0.959
1.0×10^{19}	0.953	0.951	0.949	0.947
2.5	0.908	0.904	0.898	0.894
5.0	0.862	0.853	0.843	0.834
7.5	0.831	0.818	0.804	0.792
1.0×10^{20}	0.806	0.790	0.774	0.759
2.5	0.715	0.688	0.659	0.634
5.0	0.636	0.598	0.558	0.526
7.5	0.585	0.541	0.496	0.460
1.0×10^{21}	0.548	0.500	0.450	0.413
2.5	0.422	0.364	0.309	0.272
5.0	0.321	0.262	0.211	0.178
7.5	0.261	0.205	0.159	0.129
1.0×10^{22}	0.219	0.166	0.124	9.87×10^{-2}
2.5	9.78×10^{-2}	6.23×10^{-2}	0.395×10^{-2}	2.72
5.0	3.52	1.76	0.855×10^{-3}	4.75×10^{-3}
7.5	1.48	5.90×10^{-3}	0.220	9.81×10^{-4}
1.0×10^{23}	6.74×10^{-3}	2.17	0.622×10^{-4}	2.20
2.5	1.03×10^{-4}	1.04×10^{-5}	0.620×10^{-7}	5.35×10^{-8}
5.0	1.72×10^{-7}	2.47×10^{-9}	0.102×10^{-10}	8.60×10^{-14}

TABLE (6c). EXP [− OPTICAL DEPTH] (13–0) BAND

$N(O_2)$	190 K	230 K	270 K	300 K
1.0×10^{16}	0.999	0.999	0.999	0.999
2.5	0.998	0.998	0.998	0.997
5.0	0.995	0.995	0.995	0.995
7.5	0.993	0.993	0.993	0.993
1.0×10^{17}	0.991	0.991	0.991	0.990
2.5	0.980	0.978	0.978	0.978
5.0	0.966	0.965	0.963	0.962
7.5	0.956	0.953	0.951	0.949
1.0×10^{18}	0.947	0.944	0.940	0.938
2.5	0.914	0.908	0.901	0.896
5.0	0.881	0.872	0.862	0.854
7.5	0.857	0.845	0.832	0.823
1.0×10^{19}	0.837	0.823	0.808	0.798
2.5	0.758	0.735	0.711	0.693
5.0	0.681	0.650	0.617	0.594
7.5	0.629	0.592	0.556	0.530
1.0×10^{20}	0.590	0.549	0.510	0.483
2.5	0.449	0.399	0.353	0.323
5.0	0.331	0.278	0.232	0.204
7.5	0.261	0.209	0.166	0.142
1.0×10^{21}	0.212	0.163	0.124	0.103
2.5	8.02×10^{-2}	5.01×10^{-2}	3.16×10^{-2}	2.26×10^{-2}
5.0	2.31	1.10	5.31×10^{-3}	3.17×10^{-3}
7.5	8.06×10^{-3}	3.06×10^{-3}	1.18	6.14×10^{-4}
1.0×10^{22}	3.12	9.59×10^{-4}	3.07×10^{-4}	1.41
2.5	2.27×10^{-5}	2.24×10^{-6}	2.54×10^{-7}	5.86×10^{-8}
5.0	1.54×10^{-8}	2.18×10^{-10}	3.58×10^{-12}	2.73×10^{-13}

with the determination of the photodissociation rates in the mesosphere above 70 km, since Lyman-α with a total number of photons of $(3\pm1)\times 10^{11}\,cm^{-2}\,s^{-1}$, available before their attenuation by O_2, may be important. If we use the laboratory results obtained by Carver *et al.* (1977), it is possible to deduce simple formulas. Adopting an average temperature of 190 K, we may write

$$\tau_{Ly\text{-}\alpha}(O_2) = 4.17\times10^{-19}\,N(O_2)^{0.917}, \qquad (17)$$

TABLE 7(a). ABSORPTION COEFFICIENTS OF THE SCHUMANN–RUNGE BANDS AT $T = 190$ K

Band	σ_M	σ_m	σ_M/σ_m
19–0	8.61×10^{-20}	1.20×10^{-21}	7.1523×10^{1}
18–0	1.54×10^{-19}	7.72	1.9941
17–0	1.78	4.20	4.2395
16–0	1.63	3.01	5.4203
15–0	1.40	1.07	1.3077×10^{2}
14–0	1.24	3.08×10^{-22}	4.0143
13–0	9.60×10^{-20}	2.67	3.5935
12–0	7.02	5.24	1.3387
11–0	4.83	2.98	1.6181
10–0	3.12	6.72×10^{-23}	4.6376
9–0	2.00	5.83	3.4320
8–0	1.15	4.57	2.5274
7–0	5.99×10^{-21}	2.29	2.6124
6–0	2.83	1.50	1.8819
5–0	1.14	1.34	8.4975×10^{1}
4–0	3.99×10^{-22}	1.34	2.9663
3–0	1.27	1.30	9.7606×10^{0}
2–0	3.81×10^{-23}	1.25	3.0576

TABLE 7(b). ABSORPTION COEFFICIENTS OF THE SCHUMANN–RUNGE BANDS AT $T = 230$ K

Band	σ_M	σ_m	σ_M/σ_m
19–0	7.52×10^{-20}	1.02×10^{-21}	7.3880×10^{1}
18–0	1.41×10^{-19}	7.16	1.9728
17–0	1.72	4.13	4.1529
16–0	1.64	3.40	4.8345
15–0	1.44	1.37	1.0523×10^{2}
14–0	1.28	4.60×10^{-22}	2.7870
13–0	9.91×10^{-20}	3.43	2.8864
12–0	7.14	6.01	1.1881
11–0	4.91	4.40	1.1177
10–0	3.17	1.01	3.1472
9–0	2.02	8.81×10^{-23}	2.2935
8–0	1.17	8.27	1.4100
7–0	6.06×10^{-21}	3.12	1.9402
6–0	2.86	1.82	1.5684
5–0	1.16	1.51	7.6922×10^{1}
4–0	4.05×10^{-22}	1.42	2.8497
3–0	1.29	1.31	9.8410×10^{0}
2–0	3.88×10^{-23}	1.25	3.1069

TABLE 7(c). ABSORPTION COEFFICIENTS OF THE SCHUMANN–RUNGE BANDS AT $T = 270$ K

Band	σ_M	σ_m	σ_M/σ_m
19–0	6.66×10^{-20}	8.82×10^{-22}	7.5524×10^{1}
18–0	1.30×10^{-19}	6.63×10^{-21}	1.9596
17–0	1.64	4.00	4.1026
16–0	1.64	3.35	4.8767
15–0	1.47	1.65	8.8818
14–0	1.32	5.88×10^{-22}	2.2526×10^{2}
13–0	1.02	4.33	2.3470
12–0	7.28×10^{-20}	6.79	1.0719
11–0	5.02	5.97	8.4072×10^{1}
10–0	3.24	1.58	2.0465×10^{2}
9–0	2.06	1.13	1.8237×10^{2}
8–0	1.19	1.24	9.5643×10^{1}
7–0	6.18×10^{-21}	4.24×10^{-23}	1.4580×10^{2}
6–0	2.92	2.26	1.2898
5–0	1.19	1.83	6.5271×10^{1}
4–0	4.18×10^{-22}	1.56	2.6764
3–0	1.33	1.33	1.0051
2–0	4.04×10^{-23}	1.25	3.2300×10^{0}

corresponding to a varying cross-section

$$\sigma_{Ly\text{-}\alpha}(O_2) = 4.17\times10^{-19}\,N^{-0.083}, \qquad (18)$$

for $N(O_2) > 1\times10^{19}\,cm^{-2}$. For $N(O_2) \leq 10^{19}\,cm^{-2}$, the conventional formula

$$J = \sigma q_\infty e^{-\tau}, \qquad (19)$$

can be adopted with

$$\sigma_{Ly\text{-}\alpha}(O_2) = 1\times10^{-20}\,cm^2. \qquad (20)$$

For $N(O_2) > 1\times10^{19}\,cm^2$, we write, therefore

$$J_2(Ly\text{-}\alpha) = q_\infty 4.17\times10^{-19}\,N^{-0.083}e^{-4.17\times10^{-19}N^{0.917}}, \qquad (21)$$

where q_∞ is the number of photons ($cm^{-2}\,s^{-1}$) available at the top of the Earth's atmosphere and $N \equiv N(O_2)\,cm^{-2}$. Numerical results given in Table 13 show that above 70 km (for an overhead Sun), Lyman-α, under average solar conditions, increases the O_2 photodissociation rate by about 30%. This percentage will be subject to variations due to solar activity.

The action of Lyman-α is particularly important for the photodissociation of H_2O and of CO_2. For these two molecules the Lyman-α photodissociation rate is more than 70% of the total rate for $N(O_2) \leq 2.5\times10^{20}\,cm^{-2}$ (Nicolet, 1979) and must be considered as the principal contribution to their dissociation in the upper mesosphere which will depend strongly on solar activity.

TABLE 8. COEFFICIENTS FOR DETERMINATION OF EFFECTIVE ABSORPTION CROSS-SECTIONS OF O_2 SCHUMANN–RUNGE BANDS

Band	$T = 190$ K		$T = 230$ K		$T = 270$ K	
	$p_{2,0}$	$p_{2,1}$	$p_{2,0}$	$p_{2,1}$	$p_{2,0}$	$p_{2,1}$
19–0	−27.1524	0.5950	−27.3660	0.5977	−27.2697	0.5938
18–0	−31.1457	0.7037	−31.1405	0.7022	−31.3029	0.7045
17–0	−31.4823	0.7069	−31.5985	0.7086	−31.6289	0.7984
16–0	−27.6759	0.6205	−28.2548	0.6337	−28.0735	0.6284
15–0	−26.1103	0.5822	−27.0726	0.6043	−27.7442	0.6199
14–0	−18.9317	0.4213	−19.5698	0.4363	−20.0787	0.4477
13–0	−18.3586	0.4107	−18.5631	0.4154	−19.1937	0.4296
12–0	−23.5433	0.4233	−23.3420	0.1587	−23.3534	0.5192
11–0	−26.2144	0.5699	−27.2023	0.5917	−27.5759	0.5998
10–0	−19.7291	0.4271	−20.3744	0.4415	−21.3725	0.4640
9–0	−21.3977	0.4589	−22.6718	0.4876	−23.5321	0.5061
8–0	−23.8493	0.5043	−25.3106	0.5374	−25.9939	0.5521
7–0	−24.4365	0.5118	−25.6943	0.5381	−27.0531	0.5668
6–0	−24.6454	0.5129	−24.8725	0.5169	−25.5236	0.5294
5–0	−27.7670	0.5724	−27.1231	0.5570	−27.5593	0.5642
4–0	−36.0202	0.7350	−34.5348	0.7014	−34.0160	0.6876
3–0	−37.4590	0.7631	−34.1537	0.6929	−32.3149	0.6509
2–0	−34.3023	0.6997	−30.5893	0.6222	−27.2204	0.5493

TABLE 9. PARAMETERS FOR DETERMINATION OF O_2 OPTICAL DEPTH

Band	$T = 190$ K		$T = 230$ K		$T = 270$ K	
	$d_{2,0}$	$d_{2,1}$	$d_{2,0}$	$d_{2,1}$	$d_{2,0}$	$d_{2,1}$
19–0	−22.2647	0.4938	−20.511	0.4552	−20.5433	0.4546
18–0	−26.2477	0.5914	−27.0032	0.6070	−26.8968	0.6036
17–0	−21.5859	0.4877	−21.5692	0.4874	−21.5642	0.4871
16–0	−23.1643	0.5184	−22.9975	0.5160	−23.0408	0.5176
15–0	−20.5035	0.4512	−21.2109	0.4684	−20.0262	0.4449
14–0	−22.2214	0.4747	−22.3230	0.4808	−22.1773	0.4807
13–0	−25.9567	0.5466	−26.4881	0.5608	−26.1471	0.5566
12–0	−25.7030	0.5480	−25.4172	0.5442	−25.9842	0.5575
11–0	−21.2361	0.4553	−21.9458	0.4739	−22.4196	0.4873
10–0	−25.0795	0.5159	−24.1133	0.5009	−22.6346	0.4751
9–0	−24.1337	0.4957	−23.2161	0.4803	−23.6780	0.4923
8–0	−24.3090	0.4970	−23.4269	0.4848	−24.0370	0.5015
7–0	−24.0797	0.4845	−24.7619	0.5012	−24.3381	0.4959
6–0	−28.8867	0.5697	−25.3433	0.5042	−24.9085	0.4989
5–0	−31.0862	0.6078	−30.5188	0.6000	−26.9407	0.5346
4–0	−34.4926	0.6683	−33.6523	0.6549	−33.1046	0.6474
3–0	−41.5449	0.7963	−40.7366	0.7827	−39.1489	0.7546
2–0	−49.2427	0.9377	−48.8488	0.9304	−46.8581	0.8944

TABLE 10. PHOTODISSOCIATION COEFFICIENTS OF O_2 SCHUMANN–RUNGE BANDS

Band	$T = 190$ K		$T = 230$ K		$T = 270$ K	
	$j_{SR}(O_2) = \sigma_M q_\infty$	$j_{SR}(O_2) = \sigma_m q_\infty$	$j_{SR}(O_2) = \sigma_M q_\infty$	$j_{SR}(O_2) = \sigma_m q_\infty$	$j_{SR}(O_2) = \sigma_M q_\infty$	$j_{SR}(O_2) = \sigma_m q_\infty$
19–0	1.36×10^{-9}	1.90×10^{-11}	1.19×10^{-9}	1.61×10^{-11}	1.05×10^{-9}	1.39×10^{-11}
18–0	3.43	1.72×10^{-10}	3.14	1.60×10^{-10}	2.90	1.48×10^{-10}
17–0	4.98	1.18	4.82	1.16	4.59	1.12
16–0	5.96	1.10	6.00	1.24	6.00	1.23
15–0	7.25	5.54	7.46	7.10×10^{-11}	7.61	8.55×10^{-11}
14–0	8.18	2.03	8.45	3.04	8.71	3.88
13–0	8.44	2.35	8.71	3.01	8.96	3.81
12–0	7.23	5.40	7.35	6.19	7.50	6.99
11–0	6.91	4.26	7.02	6.29	7.18	8.54
10–0	6.46	1.39	6.56	2.09	6.71	3.27
9–0	4.18	1.22	4.22	1.84	4.30	2.36
8–0	2.94	1.17	2.97	2.11	3.02	3.17
7–0	2.37	9.07×10^{-12}	2.40	1.24	2.45	1.68
6–0	1.31	6.94	1.32	8.43×10^{-12}	1.35	1.05
5–0	7.27×10^{-10}	8.55	7.40×10^{-10}	9.57	7.59×10^{-10}	1.17
4–0	2.85	9.66	2.90	1.02×10^{-11}	2.99	1.12
3–0	1.45	1.48×10^{-11}	1.47	1.49	1.52	1.52
2–0	5.87×10^{-11}	1.93	5.98×10^{-11}	1.92	6.22×10^{-11}	1.92

TABLE 11. COMPARISON OF THE O_2 OPTICAL DEPTHS DETERMINED BY DIRECT AND DETAILED CALCULATIONS (τ_d) WITH THE FORMULA WITH 2 TERMS (τ_2) AND WITH 6 TERMS (τ_6) CORRESPONDING TO EQUATIONS (15) AND (16). RESPECTIVELY. THE RATIO R_2 AND R_6 ARE ALSO GIVEN. I = 230 K

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
	$N(O_2) = 1.0 \times 10^{24}$ cm^{-2}				
6-0	2.97×10^{-10}			3.12×10^{-10}	0.95
5-0	1.01×10^{-8}			9.95×10^{-8}	1.01
4-0	4.97×10^{-8}			4.74×10^{-8}	1.05
3-0	4.55×10^{-7}			4.65×10^{-7}	0.98
2-0	1.56×10^{-6}	2.11×10^{-6}	0.74	1.52×10^{-6}	1.33
	$N(O_2) = 7.5 \times 10^{23}$ cm^{-2}				
6-0	3.25×10^{-8}			3.26×10^{-8}	1.00
5-0	5.27×10^{-7}			5.27×10^{-7}	1.00
4-0	2.18×10^{-6}			2.12×10^{-6}	1.03
3-0	1.37×10^{-5}			1.37×10^{-5}	1.00
2-0	3.96×10^{-5}	4.54×10^{-5}	0.87	3.99×10^{-5}	0.99
	$N(O_2) = 5.0 \times 10^{23}$ cm^{-2}				
6-0	3.93×10^{-6}			4.03×10^{-6}	0.98
5-0	2.95×10^{-5}			2.91×10^{-5}	1.01
4-0	1.02×10^{-4}			1.02×10^{-4}	1.00
3-0	4.29×10^{-4}			4.26×10^{-4}	1.01
2-0	1.04×10^{-3}	1.05×10^{-3}	0.98	1.02×10^{-3}	1.01
	$N(O_2) = 2.5 \times 10^{23}$ cm^{-2}				
7-0	1.04×10^{-5}			1.03×10^{-5}	1.01
6-0	6.20×10^{-4}			6.12×10^{-4}	1.01
5-0	1.98×10^{-3}	2.27×10^{-3}	0.87	1.99×10^{-3}	0.99
4-0	5.44×10^{-3}	6.08×10^{-3}	0.90	5.36×10^{-3}	1.01
3-0	1.47×10^{-2}	1.53×10^{-2}	0.96	1.48×10^{-2}	0.99
2-0	2.84×10^{-2}	2.74×10^{-2}	1.04	2.89×10^{-2}	0.98
	$N(O_2) = 1.0 \times 10^{23}$ cm^{-2}				
9-0	3.30×10^{-6}			3.25×10^{-6}	1.02
8-0	4.40×10^{-6}			4.32×10^{-6}	1.02
7-0	2.17×10^{-3}	2.60×10^{-3}	0.83	2.19×10^{-3}	0.99
6-0	1.85×10^{-2}	2.02×10^{-2}	0.91	1.85×10^{-3}	1.00
5-0	3.47×10^{-2}	2.98×10^{-2}	1.16	3.46×10^{-2}	1.00
4-0	7.03×10^{-2}	6.08×10^{-2}	1.16	7.06×10^{-2}	1.00
3-0	1.38×10^{-1}	1.30×10^{-1}	1.07	1.38×10^{-1}	1.00
2-0	2.19×10^{-1}	2.16×10^{-1}	1.01	2.18×10^{-1}	1.00
	$N(O_2) = 7.5 \times 10^{22}$ cm^{-2}				
10-0	5.27×10^{-6}			5.65×10^{-6}	0.93
9-0	4.09×10^{-5}			4.22×10^{-5}	0.96
8-0	4.62×10^{-5}			4.66×10^{-5}	0.99
7-0	5.90×10^{-3}	5.78×10^{-3}	1.02	5.95×10^{-3}	0.99
6-0	3.49×10^{-2}	3.42×10^{-2}	1.02	3.49×10^{-2}	1.00
5-0	6.03×10^{-2}	5.20×10^{-2}	1.16	6.01×10^{-2}	1.00
4-0	0.112	9.83×10^{-2}	1.14	0.112	1.00
3-0	0.206	0.196	1.05	0.206	1.00
2-0	0.310	0.309	1.00	0.311	1.00
	$N(O_2) = 5.0 \times 10^{22}$ cm^{-2}				
10-0	1.14×10^{-4}			1.16×10^{-4}	0.98
9-0	5.41×10^{-4}			5.41×10^{-4}	1.00
8-0	5.34×10^{-4}			5.29×10^{-4}	1.01
7-0	1.76×10^{-2}	1.49×10^{-2}	1.18	1.75×10^{-2}	1.00
6-0	6.96×10^{-2}	6.39×10^{-2}	1.09	6.97×10^{-2}	1.00
5-0	0.110	9.85×10^{-2}	1.12	0.110	1.01
4-0	0.185	0.169	1.10	0.185	1.00
3-0	0.314	0.305	1.03	0.313	1.00
2-0	0.443	0.447	0.99	0.443	1.00

TABLE 11. *(contd)*

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
$N(O_2) = 2.5 \times 10^{22}$ cm^{-2}					
10-0	3.32×10^{-3}	3.77×10^{-3}	0.88	3.20×10^{-3}	1.04
9-0	8.12×10^{-3}	8.79×10^{-3}	0.92	7.86×10^{-3}	1.03
8-0	7.37×10^{-3}	7.90×10^{-3}	0.93	7.23×10^{-3}	1.02
7-0	6.23×10^{-2}	5.12×10^{-2}	1.22	6.14×10^{-2}	1.02
6-0	0.156	0.144	1.09	0.158	0.99
5-0	0.223	0.217	1.03	0.223	1.00
4-0	0.326	0.323	1.01	0.324	1.00
3-0	0.494	0.502	0.98	0.494	1.00
2-0	0.640	0.656	0.98	0.641	1.00
$N(O_2) = 1.0 \times 10^{22}$ cm^{-2}					
15-0	2.10×10^{-8}			1.98×10^{-8}	1.06
14-0	3.16×10^{-4}			3.22×10^{-4}	0.98
13-0	9.59×10^{-4}			9.53×10^{-4}	1.01
12-0	7.29×10^{-5}			7.33×10^{-5}	1.00
11-0	2.65×10^{-4}			2.64×10^{-4}	1.00
10-0	3.37×10^{-2}	2.94×10^{-2}	1.15	3.39×10^{-2}	0.99
9-0	5.17×10^{-2}	4.74×10^{-2}	1.09	5.20×10^{-2}	1.00
8-0	4.80×10^{-2}	4.49×10^{-2}	1.07	4.86×10^{-2}	0.99
7-0	0.166	0.153	1.08	0.165	1.01
6-0	0.301	0.295	1.02	0.303	1.00
5-0	0.391	0.414	0.94	0.392	1.00
4-0	0.502	0.538	0.93	0.502	1.00
3-0	0.682	0.714	0.96	0.682	1.00
2-0	0.811	0.835	0.97	0.812	1.00
$N(O_2) = 7.5 \times 10^{21}$ cm^{-2}					
15-0	7.72×10^{-7}			7.83×10^{-7}	0.98
14-0	1.17×10^{-3}	1.30×10^{-3}	0.90	1.14×10^{-3}	1.02
13-0	3.06×10^{-3}	3.01×10^{-3}	1.02	3.08×10^{-3}	0.99
12-0	4.07×10^{-4}			4.04×10^{-4}	1.01
11-0	9.50×10^{-4}	1.04	0.91	9.17×10^{-4}	1.04
10-0	5.31×10^{-2}	4.72×10^{-2}	1.13	5.44×10^{-2}	0.98
9-0	7.55×10^{-2}	7.03×10^{-2}	1.07	7.66×10^{-2}	0.99
8-0	7.16×10^{-2}	6.72×10^{-2}	1.06	7.22×10^{-2}	0.99
7-0	0.205	0.197	1.04	0.204	1.00
6-0	0.349	0.348	1.00	0.349	1.00
5-0	0.442	0.476	0.93	0.442	1.00
4-0	0.551	0.598	0.92	0.552	1.00
3-0	0.727	0.764	0.95	0.727	1.00
2-0	0.847	0.871	0.97	0.846	1.00
$N(O_2) = 5 \times 10^{21}$ cm^{-2}					
15-0	2.98×10^{-5}			3.10×10^{-5}	0.96
14-0	4.66×10^{-3}	4.23×10^{-3}	1.10	4.52×10^{-3}	1.03
13-0	1.10×10^{-2}	9.81×10^{-3}	1.12	1.11×10^{-2}	0.99
12-0	2.52×10^{-3}	2.79×10^{-3}	0.90	2.50×10^{-3}	1.01
11-0	3.72×10^{-3}	3.47×10^{-3}	1.07	3.65×10^{-3}	1.02
10-0	8.95×10^{-2}	8.27×10^{-2}	1.08	9.25×10^{-2}	0.97
9-0	0.117	0.112	1.04	0.120	0.98
8-0	0.114	0.109	1.05	0.115	1.00
7-0	0.262	0.266	0.99	0.264	0.99
6-0	0.416	0.423	0.98	0.414	1.00
5-0	0.510	0.559	0.91	0.511	1.00
4-0	0.615	0.674	0.91	0.615	1.00
3-0	0.781	0.822	0.95	0.782	1.00
2-0	0.886	0.910	0.97	0.886	1.00
$N(O_2) = 2.5 \times 10^{21}$ cm^{-2}					
17-0	5.54×10^{-7}			5.62×10^{-7}	0.99
16-0	2.82×10^{-6}			2.66×10^{-6}	1.06
15-0	1.33×10^{-3}	1.54×10^{-3}	0.87	1.33×10^{-3}	1.00
14-0	2.22×10^{-2}	1.99×10^{-2}	1.12	2.22×10^{-2}	1.00
13-0	5.01×10^{-2}	4.35×10^{-2}	1.15	5.00×10^{-2}	1.00
12-0	1.98×10^{-2}	1.77×10^{-2}	1.12	1.97×10^{-2}	1.01
11-0	1.87×10^{-2}	1.69×10^{-2}	1.10	1.88×10^{-2}	0.99
10-0	0.174	0.172	1.01	0.177	0.98
9-0	0.210	0.209	1.00	0.211	1.00
8-0	0.208	0.205	1.02	0.206	1.01
7-0	0.364	0.392	0.93	0.368	0.99
6-0	0.523	0.545	0.96	0.521	1.00
5-0	0.616	0.681	0.90	0.617	1.00
4-0	0.710	0.779	0.91	0.710	1.00
3-0	0.852	0.892	0.96	0.852	1.00
2-0	0.932	0.952	0.98	0.932	1.00
$N(O_2) = 1 \times 10^{21}$ cm^{-2}					
19-0	1.02×10^{-2}	1.13×10^{-2}	0.91	1.04×10^{-2}	0.99
18-0	1.55×10^{-5}	(2.[illegible]x10^{-5})	(0.53)	1.53×10^{-5}	1.01
17-0	4.67×10^{-4}	(6.24×10^{-4})	(0.75)	4.79×10^{-4}	0.98
16-0	7.89×10^{-4}	8.73×10^{-4}	0.90	7.65×10^{-4}	1.03
15-0	1.76×10^{-2}	1.47×10^{-2}	1.19	1.75×10^{-2}	1.00
14-0	8.08×10^{-2}	8.04×10^{-2}	1.00	8.20×10^{-2}	0.99
13-0	0.163	0.153	1.06	0.162	1.00
12-0	9.40×10^{-2}	8.63×10^{-2}	1.09	9.44×10^{-2}	1.00
11-0	7.34×10^{-2}	7.12×10^{-2}	1.03	7.34×10^{-2}	1.00
10-0	0.313	0.328	0.95	0.312	1.00
9-0	0.355	0.365	0.97	0.351	1.01
8-0	0.353	0.362	0.97	0.350	1.01
7-0	0.500	0.553	0.90	0.502	1.00
6-0	0.651	0.682	0.95	0.649	1.00
5-0	0.733	0.801	0.92	0.733	1.00
4-0	0.813	0.872	0.93	0.813	1.00
3-0	0.917	0.946	0.97	0.916	1.00
2-0	0.968	0.979	0.99	0.967	1.00
$N(O_2) = 7.50 \times 10^{20}$ cm^{-2}					
19-0	1.66×10^{-2}	1.96×10^{-2}	0.85	1.78×10^{-2}	0.94
18-0	1.15×10^{-4}	(1.55×10^{-4})	(0.74)	1.14×10^{-4}	1.01
17-0	1.57×10^{-3}	1.64×10^{-3}	0.96	1.55×10^{-3}	1.01
16-0	2.29×10^{-3}	2.31×10^{-3}	0.99	2.24×10^{-3}	1.02
15-0	2.92×10^{-2}	2.51×10^{-2}	1.16	2.90×10^{-2}	1.01
14-0	0.110	0.111	0.99	0.111	0.99
13-0	0.209	0.203	1.03	0.208	1.00
12-0	0.131	0.123	1.06	0.132	1.00
11-0	0.101	9.98×10^{-2}	1.01	0.100	1.00
10-0	0.360	0.382	0.94	0.358	1.00
9-0	0.401	0.415	0.97	0.398	1.01
8-0	0.329	0.413	0.97	0.397	1.01
7-0	0.542	0.599	0.90	0.542	1.00
6-0	0.687	0.718	0.96	0.686	1.00
5-0	0.765	0.830	0.92	0.764	1.00
4-0	0.840	0.893	0.94	0.840	1.00
3-0	0.932	0.957	0.97	0.931	1.00
2-0	0.975	0.984	0.99	0.975	1.00

TABLE 11. (*contd*)

$N(O_2) = 5.00 \times 10^{20}$ cm^{-2}

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
19-0	3.22×10^{-2}	3.80×10^{-2}	0.85	3.35×10^{-2}	0.96
18-0	1.00×10^{-3}	1.05×10^{-3}	0.95	1.00×10^{-3}	1.00
17-0	5.66×10^{-3}	5.18×10^{-3}	1.09	5.53×10^{-3}	1.02
16-0	7.45×10^{-3}	7.26×10^{-3}	1.03	7.34×10^{-3}	1.02
15-0	5.18×10^{-2}	4.74×10^{-2}	1.09	5.20×10^{-2}	1.00
14-0	0.160	0.164	0.98	0.159	1.00
13-0	0.278	0.280	0.99	0.278	1.00
12-0	0.192	0.186	1.03	0.192	1.00
11-0	0.147	0.149	0.98	0.145	1.01
10-0	0.427	0.455	0.94	0.422	1.01
9-0	0.466	0.485	0.96	0.462	1.01
8-0	0.463	0.484	0.96	0.462	1.00
7-0	0.598	0.658	0.91	0.597	1.00
6-0	0.734	0.764	0.96	0.734	1.00
5-0	0.805	0.864	0.93	0.804	1.00
4-0	0.875	0.916	0.96	0.874	1.00
3-0	0.950	0.968	0.98	0.948	1.00
2-0	0.982	0.989	0.99	0.982	1.00

$N(O_2) = 2.50 \times 10^{20}$ cm^{-2}

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
19-0	8.84×10^{-2}	9.20×10^{-2}	0.96	8.49×10^{-2}	1.04
18-0	1.21×10^{-2}	1.11×10^{-2}	1.09	1.20×10^{-2}	1.01
17-0	2.43×10^{-2}	2.34×10^{-2}	1.04	2.44×10^{-2}	0.99
16-0	3.21×10^{-2}	3.19×10^{-2}	1.01	3.22×10^{-2}	1.00
15-0	0.107	0.110	0.97	0.109	0.98
14-0	0.264	0.274	0.96	0.261	1.01
13-0	0.399	0.422	0.94	0.401	1.00
12-0	0.317	0.316	1.00	0.310	1.02
11-0	0.243	0.254	0.96	0.242	1.00
10-0	0.539	0.574	0.94	0.531	1.02
9-0	0.572	0.596	0.96	0.569	1.00
8-0	0.568	0.595	0.96	0.570	1.00
7-0	0.688	0.744	0.92	0.685	1.00
6-0	0.805	0.827	0.97	0.807	1.00
5-0	0.864	0.908	0.95	0.863	1.00
4-0	0.923	0.946	0.98	0.925	1.00
3-0	0.972	0.981	0.99	0.971	1.00
2-0	0.991	0.994	1.00	0.100	0.99

$N(O_2) = 1.00 \times 10^{20}$ cm^{-2}

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
19-0	0.225	0.208	1.08	0.213	1.06
18-0	7.82×10^{-2}	7.56×10^{-2}	1.03	7.82×10^{-2}	1.00
17-0	8.47×10^{-2}	9.05×10^{-2}	0.94	8.65×10^{-2}	0.98
16-0	0.114	0.117	0.98	0.113	1.02
15-0	0.215	0.238	0.90	0.216	0.99
14-0	0.418	0.435	0.96	0.416	1.00
13-0	0.549	0.597	0.92	0.552	1.00
12-0	0.471	0.497	0.95	0.469	1.00
11-0	0.390	0.412	0.95	0.392	1.00
10-0	0.670	0.704	0.95	0.667	1.00
9-0	0.693	0.716	0.97	0.695	1.00
8-0	0.693	0.717	0.97	0.696	1.00
7-0	0.790	0.830	0.95	0.787	1.00
6-0	0.878	0.887	0.99	0.881	1.00
5-0	0.923	0.946	0.98	0.922	1.00
4-0	0.964	0.970	0.99	0.964	1.00
3-0	0.988	0.991	1.00	0.989	1.00
2-0	0.996	0.998	1.00	1.000	1.00

$N(O_2) = 7.50 \times 10^{19}$ cm^{-2}

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
19-0	0.277	0.252	1.10	0.269	1.03
18-0	0.115	0.114	1.01	0.115	1.01
17-0	0.116	0.124	0.93	0.117	0.99
16-0	0.153	0.157	0.98	0.152	1.01
15-0	0.257	0.286	0.90	0.256	1.00
14-0	0.467	0.484	0.97	0.467	1.00
13-0	0.593	0.645	0.92	0.595	1.00
12-0	0.518	0.550	0.94	0.516	1.00
11-0	0.439	0.461	0.95	0.441	1.00
10-0	0.705	0.738	0.96	0.704	1.00
9-0	0.727	0.748	0.97	0.729	1.00
8-0	0.728	0.749	0.97	0.731	1.00
7-0	0.818	0.851	0.96	0.816	1.00
6-0	0.896	0.902	0.99	0.900	1.00
5-0	0.937	0.954	0.98	0.937	1.00
4-0	0.972	0.975	1.00	0.973	1.00
3-0	0.991	0.993	1.00	1.000	0.99
2-0	0.997	0.998	1.00	1.000	1.00

$N(O_2) = 5.00 \times 10^{19}$ cm^{-2}

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
19-0	0.354	0.318	1.12	0.351	1.01
18-0	0.179	0.184	0.98	0.180	1.00
17-0	0.170	0.180	.94	0.169	1.01
16-0	0.217	0.223	0.97	0.216	1.01
15-0	0.323	0.355	0.91	0.320	1.01
14-0	0.536	0.550	0.97	0.536	1.00
13-0	0.650	0.705	0.92	0.650	1.00
12-0	0.580	0.619	0.94	0.578	1.00
11-0	0.507	0.528	0.96	0.508	1.00
10-0	0.751	0.780	0.96	0.755	1.00
9-0	0.770	0.787	0.98	0.774	0.99
8-0	0.774	0.788	0.98	0.777	1.00
7-0	0.853	0.876	0.97	0.852	1.00
6-0	0.918	0.919	1.00	0.922	1.00
5-0	0.954	0.964	0.99	0.954	1.00
4-0	0.981	0.981	1.00	0.982	1.00
3-0	0.994	0.995	1.00	1.000	0.99
2-0	0.998	0.999	1.00	1.000	1.00

$N(O_2) = 2.50 \times 10^{19}$ cm^{-2}

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
19-0	0.489	0.433	1.13	0.502	0.98
18-0	0.313	0.329	0.95	0.313	1.00
17-0	0.288	0.295	0.98	0.283	1.02
16-0	0.344	0.350	0.98	0.344	1.00
15-0	0.447	0.473	0.95	0.439	1.02
14-0	0.645	0.652	0.99	0.646	1.00
13-0	0.735	0.789	0.93	0.733	1.00
12-0	0.673	0.720	0.94	0.674	1.00
11-0	0.619	0.631	0.98	0.620	1.00
10-0	0.817	0.839	0.97	0.827	0.99
9-0	0.832	0.842	0.99	0.838	0.99
8-0	0.843	0.844	1.00	0.844	1.00
7-0	0.904	0.911	0.99	0.904	1.00
6-0	0.949	0.942	1.01	0.949	1.00
5-0	0.974	0.976	1.00	0.976	1.00
4-0	0.990	0.988	1.00	1.000	0.99
3-0	0.997	0.997	1.00	1.000	1.00
2-0	1.000	0.999	1.00	1.000	1.00

TABLE 11. (*contd*)

Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6	Band	$e^{-\tau_d(O_2)}$	$e^{-\tau_2(O_2)}$	R_2	$e^{-\tau_6(O_2)}$	R_6
		$N(O_2) = 1.00 \times 10^{19}$ cm^{-2}									
19-0	0.657	0.576	1.14	0.676	0.97	10-0	0.884	0.895	0.99	0.894	0.99
18-0	0.508	0.528	0.96	0.507	1.00	9-0	0.897	0.895	1.00	0.900	1.00
17-0	0.473	0.458	1.03	0.470	1.01	8-0	0.914	0.897	1.02	0.912	1.00
16-0	0.523	0.520	1.01	0.526	1.00	7-0	0.951	0.943	1.01	0.953	1.00
15-0	0.610	0.614	0.99	0.608	1.00	6-0	0.976	0.963	1.01	0.972	1.00
14-0	0.764	0.759	1.01	0.765	1.00	5-0	0.989	0.986	1.00	0.991	1.00
13-0	0.823	0.868	0.95	0.820	1.00	4-0	0.996	0.993	1.00	1.000	1.00
12-0	0.775	0.819	0.95	0.778	1.00	3-0	1.000	0.999	1.00	1.000	1.00
11-0	0.752	0.742	1.01	0.752	1.00	2-0	1.000	1.000	1.00	1.000	1.00

TABLE 12. PHOTODISSOCIATION RATES OF MOLECULAR OXYGEN FOR $T = 230$ K

	Detailed calculation			Formula: 2 terms	
$N(O_2)$ (cm^{-2})	Herzberg continuum*	Schumann–Range bands	J(s^{-1})	Schumann–bands	Total
1.0×10^{19}	8.38×10^{-10}	1.45×10^{-8}	1.53×10^{-8}	1.46×10^{-8}	1.54×10^{-8}
2.5	8.38	7.94×10^{-9}	8.78×10^{-9}	8.41×10^{-9}	9.25×10^{-9}
5.0	8.38	4.78	5.62	5.29	6.12
7.5	8.38	3.54	4.38	3.97	4.81
1.0×10^{20}	8.37	2.86	3.70	3.22	4.06
2.5	8.36	1.43	2.27	1.62	2.46
5.0	8.34	8.19×10^{-10}	1.65	9.40×10^{-10}	1.77
7.5	8.30	5.83	1.41	6.78	1.57
1.0×10^{21}	8.27	4.57	1.28	5.36	1.36
2.5	7.95	2.09	1.00	2.51	1.05
5.0	7.20	1.17	8.37×10^{-10}	1.41	8.62×10^{-10}
7.5	6.20	0.84	7.04	1.00	7.21
1.0×10^{22}	4.71	0.64	5.35	7.58×10^{-11}	5.46
2.5	2.16	0.27	2.43	3.02	2.47
5.0	8.35×10^{-11}	1.10×10^{-11}	9.45×10^{-11}	1.14	9.49×10^{-11}
7.5	4.17	0.54	4.71	5.38×10^{-12}	4.71
1.0×0^{23}	1.90	0.25	2.15	2.47	2.15
2.5	1.20×10^{-12}	0.11×10^{-12}	1.31×10^{-12}	1.11×10^{-13}	1.31×10^{-12}
5.0	4.61×10^{-12}	0.20×10^{-14}	4.81×10^{-14}	2.46×10^{-15}	4.85×10^{-14}
7.5	3.12×10^{-15}	0.06×10^{-15}	3.18×10^{-15}	1.02×10^{-16}	3.22×10^{-15}
1.0×10^{24}	2.50×10^{-16}	0.02×10^{-16}	2.52×10^{-16}	5.07×10^{-17}	2.56×10^{-16}

TABLE 13. EFFECT OF THE LYMAN-ALPHA RADIATION ON THE O_2 PHOTODISSOCIATION RATE J_2

$N(O_2)$	J(Ly-α) (s^{-1})	J_2(total) (s^{-1})
1.0×10^{19}	2.72×10^{-9}	1.80×10^{-8}
2.5	2.33	1.12
5.0	1.82	7.44×10^{-9}
7.5	1.41	5.79
1.0×10^{20}	1.10	4.80
2.5	7.0×10^{-10}	2.97
5.0	4.5×10^{-11}	1.75
7.5	8.0×10^{-12}	1.41

REFERENCES

Ackerman, M. and Biaumé, F. (1970). Structure of the Schumann–Runge bands from the (0–0) to the (13–0) band. *J. molec. Spectrosc.* **35,** 73.

Ackerman, M., Biaumé, F. and Kockarts, G. (1970). Absorption cross-sections of the Schumann–Runge bands of molecular oxygen. *Planet. Space Sci.* **18,** 1639.

Ackerman, M., Biaumé, F. and Nicolet, M. (1969). Absorption in the spectral range of the Schumann–Runge bands, *Can. J. Chem.* **47,** 1834.

Allison, A. C., Dalgarno, A. and Pasachoff, N. W. (1971). Absorption by vibrationally excited molecular oxygen in the Schumann–Runge continuum. *Planet. Space Sci.* **19,** 1463.

Bergeman, T. H. and Wofsy, S. C. (1972). The fine structure of $O_2(B^3\Sigma)$ *Chem. Phys. Lett.* **15,** 104.

Biaumé, F. (1972a). Détermination de la valeur absolue de l'absorption dans les bandes du système de Schumann–Runge de l'oxygène moléculaire. *Aeron. Acta Brussels* A **100**.

Biaumé, F. (1972b). Structure de rotation des bandes (0–0) à (13–0) du système de Schumann–Runge de la molécule d'oxygène. *Acad. R. Belg. Mém. Cl. Sci.* **40,** 66.

Betke, G. W. (1959). Oscillator strengths in the far u.v.—II. Oxygen Schumann–Runge bands. *J. chem. Phys.* **31,** 669.

Blake, A. J. (1979). An atmospheric absorption model for the Schumann–Runge bands of oxygen. *J. geophys. Res.* **84,** 3272.

Brix, P. and Herzberg, G. (1954). Fine structure of the Schumann–Runge bands near the convergence limit and the dissociation energy of the oxygen molecule. *Can. J. Phys.* **32,** 110.

Cann, M. W. P., Nicholls, R. W., Evans, W. F. J., Kohl, J. L., Kurnez, R., Parkinson, W. H. and Reeves, E. M. (1979). High resolution atmospheric transmission calculations down to 287 km in the 200–243 nm spectral range. *Appl. Optics* **18,** 964.

Carver, J. H., Gies, H. P., Hobbs, T. I., Lewis, B. R. and McCoy, D. G. (1977). Temperature dependence of the molecular oxygen photoabsorption cross-section near the H Lyman-alpha line. *J. geophys. Res.* **82,** 1955.

Fang, T. M., Wofsy, S. C. and Dalgarno, A. (1974). Opacity distribution functions and absorption in the Schumann–Runge bands of molecular oxygen. *Planet. Space Sci.* **22,** 413.

Farmer, A. J. D., Fabian, W., Lewis, B. R., Lonan, K. H. and Haddad, G. N. (1968). *J. quant. Spectrosc. Rad. Trans.* **8,** 1739.

Frederick, J. E. and Hudson, R. D. (1979). Predissociation linewidths and oscillator strengths for the (2–0) to (13–0) Schumann–Runge bands of O_2. *J. molec. Spectrosc.* **74,** 247.

Halmann, M. (1966). Isotope effects on Franck–Condon factors—VI. Pressure-broadened absorption intensities of the Schumann–Runge bands of $^{16}O_2$ and $^{18}O_2$. *J. chem. Phys.* **44,** 2406.

Hudson, R. D. and Carter, V. L. (1968). Absorption of oxygen at elevated temperatures (300–900 K) in the Schumann–Runge system. *J. Opt. Soc. Am.* **58,** 1621.

Hudson, R. D. and Carter, V. L. (1969). Absorption in the spectral range of the Schumann–Runge bands. *Can. J. Chem.* **47,** 1840.

Hudson, R. D., Carter, V. L. and Breig, E. L. (1969). Predissociation in the Schumann–Runge band system of O_2: laboratory measurements and atmospheric effects. *J. geophys. Res.* **74,** 4079.

Hudson, R. D. and Mahle, S. H. (1972). Photodissociation rates of molecular oxygen in the mesosphere and lower thermosphere. *J. geophys. Res.* **77,** 2902.

Husson, V., Hebert, G. R. and Nicholls, R. W. (1970). Measured transition probabilities for bands of the Schumann–Runge $(B^2\Sigma–X^3\Sigma)$ band system of molecular oxygen. *J. Phys. B. Atomic Molec. Phys,* **3,** 1188.

Huebner, R. H., Colette, R. J., Mielczarek, S. R. and Kuyat, C. E. (1975). Apparent oscillator strength for molecular oxygen derived from electron energy loss measurements. *J. chem. Phys.* **63,** 241.

Julienne, P. S. (1976). $^3\Sigma_u^-–^3\Sigma_u^+$ coupling in the $O_2B^3\Sigma_u^-$ predissociation. *J. molec. Spectrosc.* **63,** 60.

Kockarts, G. (1971). Penetration of solar radiation in the Schumann–Runge bands of molecular oxygen, in *Mesospheric Models and Related Experiments* (Ed. G. Fiocco), pp. 160–176. Reidel, Dordrecht, Holland.

Kockarts, G. (1976). Absorption and photodissociation in the Schumann–Runge bands of molecular oxygen in the terrestrial atmosphere. *Planet. Space Sci.* **24,** 589.

Lewis, B. R., Carver, J. H., Hobbs, T. I., McCoy D. G. and Gies, H. P. F. (1978). Experimentally determined oscillator strengths and linewidths for the Schumann–Runge band system of molecular oxygen—I. The (6–0) (14–0) bands. *J. quant. Spectrosc. Rad. Trans.* **20,** 191.

Lewis, G. R., Carver, J. H., Hobbs, T. I., McCoy, D. G. and Giess, H. P. F. (1979). Experimentally determined oscillator strengths and linewidths for the Schumann–Runge band system of molecular oxygen, II The (2–0) to (5–0) bands. *J. quant. Spectrosc. Rad. Trans.* **21,** 213.

Logan, J. A., Prather, M. J., Wofsy, S. C. and McElroy, M. B. (1978). Atmospheric chemistry: response to human influence. *Phil. Trans. R. Soc. London* **A290,** 187.

Muramatsu, H. (1975). Dissociation rates of oxygen and ozone molecules in the stratosphere and mesosphere, *Papers in Meteorology and Geophysics* **26,** 219.

Nicolet, M. Solar u.v. radiation and its absorption in the mesosphere and stratosphere. *Pure appl. Geophys.* To be published.

Park, J. H. (1974). The equivalent mean absorption cross-sections for the O_2 Schumann–Runge bands: application to the H_2O and NO photodissociation rates. *J. Atmos. Sci.* **31,** 1893.

Shimazaki, T., Ogawa, T. and Farrell, B. C. (1977). Simplified methods for calculating photodissociation rates of various molecules in the Schumann–Runge band systems in the upper atmosphere. MSAA Tech. Note TN D-8399.