Chapter 9
The Upper Atmosphere

9.1 Introduction

Conditions in the outermost region of the atmosphere differ radically from those in the lower atmosphere. The principal characteristic features are the following:

1. Because of the low density, eddy diffusion as a mechanism of vertical transport ceases to be important at altitudes above 100 km, and molecular diffusion becomes the main mode of transport. As a consequence, the components of air are no longer well mixed. Atoms and molecules develop individual scale heights determined by molecular mass, which leads to separation by diffusion in the Earth's gravitational field, such that the lighter species become more abundant with increasing altitude compared to heavier species, until ultimately hydrogen, helium and atomic oxygen are the dominant constituents at high altitudes. The transition region between turbulent mixing and molecular diffusion near 100 km altitude is called the *turbopause* or *homopause*. It can be made evident by the release of luminous substances from rockets. Below the turbopause the trails are confined to a narrow ribbon, usually strongly perturbed by horizontal winds, whereas above it they become diffuse and spread with increasing altitude like a smoke plume.
2. The absorption of solar radiation in the far ultraviolet region of the spectrum occurs at altitudes greater than 100 km. This radiation causes the photodissociation of oxygen, carbon dioxide and water vapor. Only molecular nitrogen remains present mainly in molecular form as no efficient photodissociation mechanism exists.
3. The lack of molecular species capable of emitting infrared radiation prevents an efficient dissipation of thermal energy by radiation. Heat must be conducted downward into regions of the mesosphere where carbon dioxide and water vapor are sufficiently abundant to allow the removal of excess energy by radiation to space. Consequently, temperature rises strongly with increasing altitude toward values between 700 and 2,000 K in the exosphere, depending on solar activity. This part of the atmosphere is called the *Thermosphere*. Solar radiation in the extreme ultraviolet varies considerably with solar activity. Temperatures in the

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thermosphere vary accordingly, approaching low values at solar minimum and high values at solar maximum.

4. Extreme ultraviolet radiation from the sun also causes atoms and molecules to undergo photoionization, which produces electron densities up to some 10^6 cm^{-3} at altitudes near 300 km. The phenomenon is known as the *Ionosphere*. Its presence was originally inferred from the reflection of radio-waves back to earth, and prior to the advent of rockets and satellites, radio waves provided the only means of exploring electron densities in the ionosphere. Individual layers that were discerned with increasing altitude were named D, E, and F, a nomenclature still used today. At frequencies up to 4.4 MHz, radio waves are reflected from the E-layer at altitudes near 100 km. Wave penetration to the F-layer occurs at greater frequencies. During daytime the F-layer usually is split into a lower layer labeled F1 and a higher layer F2, but the F1 ledge disappears at night.

   The primary ions generated from nitrogen and oxygen in the region >100 km are N_2^+, O_2^+ and O^+. These ions enter into reactions with neutral species so that the stationary ion composition differs from that produced originally. For example, NO^+ is a prominent product appearing in the E-layer region. The loss of ions by ion-electron recombination occurs mainly via molecular ions, because only these allow excess energy to be released by dissociation, whereas the recombination of atomic ions requires energy release by radiation. Dissociative recombination is by several orders of magnitude more efficient than that of radiative recombination. The ionosphere extends downward to altitudes <100 km, with lower ion densities and different ion chemistry. Here, ionization occurs by solar X-rays, by ionization of NO via the solar Lyman a line, which penetrates deeper into the atmosphere due to a spectral window at 126 nm, and by cosmic rays. In this region, electrons attach to molecules whereby negative ions are formed that also enter into reactions with neutral molecules. These reactions give rise to a more complex ion chemistry.
5. The upper atmosphere also is the location of airglow phenomena; this includes a number of weak emission spectra only visible at night, although they are present much more strongly during the day, and quite spectacular displays of aurorae. Examples of airglow features in the mesosphere are emissions from long-lived molecular oxygen excited to the $^1\Delta_g$ state and vibrational excited OH molecules that emit the Meinel bands. Resonance emission from the sodium line at ~589 nm also occurs owing to a chemiluminescence reaction.

In the auroral region, energetic electrons, protons and heavier charged species precipitate into the atmosphere along magnetic field lines to produce sporadic ionization and excitation of atoms and molecules. Auroral lights are observed predominantly in circular belts between 15° and 30° from the geomagnetic poles in both hemispheres of the earth. The emissions derive from the excitation of oxygen and nitrogen at altitudes around 100 km, with the green and red lines of atomic oxygen being most prominent. Particles responsible for the excitation are projected from the sun. They originate from solar flares that liberate protons as well as electromagnetic radiation in the X-ray region.

9.2 Physical Conditions in the Thermosphere

The US Standard Atmosphere 1976 is an idealized steady state representation of Earth's atmosphere at 45° latitude (COESA 1976). Data in Tables 9.1 and 9.2 refer to conditions of mean solar activity. The subsequent Tables 9.3a–9.3f describe models of the thermosphere for different thermopause temperatures (Banks and Kockarts 1973).

Table 9.1 Temperature T, pressure p, density ρ, number concentration n, molar mass M and pressure scale height H_p as a function of geometric altitude in the thermosphere[a]

z (km)	T (K)	p (hPa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)
86	186.87	3.734 (–3)	6.958 (–6)	1.447 (20)	28.95	5.621
90	186.87	1.836 (–3)	3.416 (–6)	7.116 (19)	28.91	5.636
95	188.42	7.597 (–4)	1.393 (–6)	2.920 (19)	28.73	5.727
100	195.08	3.201 (–4)	5.604 (–7)	1.189 (19)	28.40	6.009
105	208.84	1.448 (–4)	2.325 (–7)	5.021 (18)	27.88	6.561
110	240.00	7.104 (–5)	9.708 (–8)	2.144 (18)	27.27	7.723
115	300.00	4.010 (–5)	4.289 (–8)	9.681 (17)	26.68	9.882
120	360.00	2.538 (–5)	2.222 (–8)	5.107 (17)	26.20	12.091
125	417.23	1.735 (–5)	1.291 (–8)	3.013 (17)	25.80	14.254
130	469.27	1.251 (–5)	8.152 (–9)	1.930 (17)	25.44	16.288
135	516.59	9.357 (–6)	5.465 (–9)	1.312 (17)	25.09	18.208
140	559.63	7.203 (–6)	3.831 (–9)	9.322 (16)	24.75	20.025
145	598.78	5.669 (–6)	2.781 (–9)	6.858 (16)	24.42	21.746
150	634.39	4.542 (–6)	2.076 (–9)	5.186 (16)	24.10	23.380
155	666.80	3.693 (–6)	1.585 (–9)	4.012 (16)	23.79	24.934
160	696.29	3.040 (–6)	1.233 (–9)	3.162 (16)	23.49	26.414
165	723.18	2.528 (–6)	9.750 (–10)	2.532 (16)	23.19	27.826
170	747.57	2.121 (–6)	7.815 (–10)	2.055 (16)	22.90	29.175
175	769.81	1.794 (–6)	6.339 (–10)	1.688 (16)	22.62	30.466
180	790.07	1.527 (–6)	5.194 (–10)	1.400 (16)	22.34	31.703
185	808.51	1.308 (–6)	4.295 (–10)	1.172 (16)	22.07	32.890
190	825.31	1.127 (–6)	3.581 (–10)	9.887 (15)	21.81	34.030
195	840.62	9.749 (–7)	3.006 (–10)	8.400 (15)	21.55	35.127
200	854.56	8.474 (–7)	2.541 (–10)	7.182 (15)	21.30	36.183
210	878.84	6.476 (–7)	1.846 (–10)	5.337 (15)	20.83	38.182
220	899.01	5.015 (–7)	1.367 (–10)	4.040 (15)	20.37	40.043
230	915.78	3.928 (–7)	1.029 (–10)	3.106 (15)	19.95	41.781
240	929.73	3.106 (–7)	7.858 (–11)	2.420 (15)	19.56	43.405
250	941.33	2.477 (–7)	6.073 (–11)	1.906 (15)	19.19	44.924
260	950.99	1.989 (–7)	4.742 (–11)	1.515 (15)	18.85	46.346
270	959.04	1.608 (–7)	3.738 (–11)	1.215 (15)	18.53	47.678
280	965.75	1.308 (–7)	2.971 (–11)	9.807 (14)	18.24	48.925
290	971.34	1.069 (–7)	2.378 (–11)	7.967 (14)	17.97	50.095
300	976.01	8.770 (–8)	1.916 (–11)	6.509 (14)	17.73	51.193

(continued)

Table 9.1 (continued)

z (km)	T (K)	p (hPa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)
320	983.16	5.980 (−8)	1.264 (−11)	4.405 (14)	17.29	53.199
340	988.15	4.132 (−8)	8.503 (−12)	3.029 (14)	16.91	54.996
360	991.65	2.888 (−8)	5.805 (−12)	2.109 (14)	16.57	56.637
380	994.10	2.038 (−8)	4.013 (−12)	1.485 (14)	16.27	58.178
400	995.83	1.452 (−8)	2.803 (−12)	1.056 (14)	15.98	59.678
450	998.22	6.447 (−9)	1.184 (−12)	4.678 (13)	15.25	63.644
500	999.24	3.024 (−9)	5.215 (−13)	2.192 (13)	14.33	68.785
600	999.85	8.213 (−10)	1.137 (−13)	5.950 (12)	11.51	88.244
700	999.97	3.191 (−10)	3.070 (−14)	2.311 (12)	8.00	130.630
800	999.99	1.704 (−10)	1.136 (−14)	1.234 (12)	5.54	193.862
900	1000.0	1.087 (−10)	5.759 (−15)	7.876 (11)	4.40	250.894
1,000	1000.0	7.514 (−11)	3.561 (−15)	5.442 (11)	3.94	286.203

[a]Powers of ten are shown in parentheses

Table 9.2 Atmospheric composition in the thermosphere (unit: m^{-3})[a]

Altitude	N_2	O_2	O	Ar	He	H
86	1.130 (20)	3.031 (19)	8.600 (16)	1.351 (18)	7.582 (14)	–
90	5.547 (19)	1.479 (19)	2.443 (17)	6.574 (17)	3.976 (14)	–
95	2.268 (19)	5.830 (18)	4.365 (17)	2.583 (17)	1,973 (14)	–
100	9.210 (18)	2.151 (18)	4.298 (17)	9.501 (16)	1.133 (14)	–
105	3.883 (18)	7.645 (17)	3.406 (17)	3.299 (16)	7.633 (13)	–
110	1.641 (18)	2.621 (17)	2.303 (17)	1.046 (16)	5.821 (13)	–
115	7.254 (17)	9.646 (16)	1.305 (17)	3.386 (15)	4.646 (13)	–
120	3.726 (17)	4.395 (16)	9.275 (16)	1.366 (15)	3.888 (13)	–
125	2.135 (17)	2.336 (16)	6.376 (16)	6.498 (14)	3.356 (13)	–
130	1.326 (17)	1.375 (16)	4.625 (16)	3.458 (14)	2.972 (13)	–
135	8.735 (16)	8.645 (15)	3.497 (16)	1.985 (14)	2.679 (13)	–
140	6.009 (16)	5.702 (15)	2.729 (16)	1.205 (14)	2.449 (13)	–
145	4.275 (16)	3.903 (15)	2.183 (16)	7.630 (13)	2.261 (13)	–
150	3.142 (16)	2.750 (15)	1.780 (16)	5.000 (13)	2.106 (13)	3.767 (11)
155	2.333 (16)	1.984 (15)	1.475 (16)	3.368 (13)	1.974 (13)	3.283 (11)
160	1.774 (16)	1.460 (15)	1.238 (16)	2.321 (13)	1.861 (13)	2.911 (11)
165	1.369 (16)	1.092 (15)	1.050 (16)	1.630 (13)	1.763 (13)	2.619 (11)
170	1.070 (16)	8.277 (14)	8.996 (15)	1.163 (13)	1.676 (13)	2.386 (11)
175	8.452 (15)	6.350 (14)	7.765 (15)	8.417 (12)	1.599 (13)	2.197 (11)
180	6.740 (15)	4.921 (14)	6.747 (15)	6.162 (12)	1.530 (13)	2.041 (11)
185	5.417 (15)	3.847 (14)	5.897 (15)	4.558 (12)	1.467 (13)	1.911 (11)
190	4.385 (15)	3.031 (14)	5.181 (15)	3.401 (12)	1.410 (13)	1.802 (11)
195	3.572 (15)	2.404 (14)	4.572 (15)	2.558 (12)	1.358 (13)	1.709 (11)
200	2.925 (15)	1.918 (14)	4.050 (15)	1.938 (12)	1.310 (13)	1.630 (11)
210	1.989 (15)	1.239 (14)	3.211 (15)	1.131 (12)	1.224 (13)	1.501 (11)
220	1.373 (15)	8.145 (13)	2.573 (15)	6.737 (11)	1.149 (13)	1.402 (11)
230	9.600 (14)	5.425 (13)	2.081 (15)	4.075 (11)	1.083 (13)	1.324 (11)
240	6.778 (14)	3.653 (13)	1.695 (15)	2.497 (11)	1.023 (13)	1.261 (11)

(continued)

Table 9.2 (continued)

Altitude	N_2	O_2	O	Ar	He	H
250	4.826 (14)	2.482 (13)	1.388 (15)	1.546 (11)	9.690 (12)	1.210 (11)
260	3.459 (14)	1.700 (13)	1.143 (15)	9.658 (10)	9.196 (12)	1.167 (11)
270	2.494 (14)	1.171 (13)	9.447 (14)	6.078 (10)	8.743 (12)	1.131 (11)
280	1.806 (14)	8.110 (12)	7.834 (14)	3.850 (10)	8.322 (12)	1.100 (11)
290	1.314 (14)	5.643 (12)	6.516 (14)	2.451 (10)	7.931 (12)	1.073 (11)
300	9.593 (13)	3.942 (12)	5.433 (14)	1.568 (10)	7.566 (12)	1.049 (11)
320	5.158 (13)	1.942 (12)	3.800 (14)	6.493 (9)	6.901 (12)	1.008 (11)
340	2.800 (13)	9.674 (11)	2.675 (14)	2.723 (9)	6.310 (12)	9.741 (10)
360	1.532 (13)	4.859 (11)	1.893 (14)	1.154 (9)	5.779 (12)	9.450 (10)
380	8.434 (12)	2.459 (11)	1.344 (14)	4.932 (8)	5.301 (12)	9.193 (10)
400	4.669 (12)	1.252 (11)	9.584 (13)	2.124 (8)	4.868 (12)	8.960 (10)
450	1.086 (12)	2.368 (10)	4.164 (13)	2.658 (7)	3.948 (12)	8.448 (10)
500	2.592 (11)	4.607 (9)	1.836 (13)	3.445 (6)	3.215 (12)	8.000 (10)
600	1.575 (10)	1.880 (8)	3.707 (12)	6.351 (4)	2.154 (12)	7.231 (10)
700	1.038 (9)	8.410 (6)	7.840 (11)	1.313 (3)	1.461 (12)	6.556 (10)
800	7.377 (7)	4.105 (5)	1.732 (11)	3.027 (1)	1.001 (12)	5.961 (10)
900	5.641 (6)	2.177 (4)	3.989 (10)	7.742 (−1)	6.933 (11)	5.434 (10)
1,000	4.626 (5)	1.251 (3)	9.562 (9)	2.188 (−2)	4.850 (11)	4.967 (10)

[a]Powers of ten are shown in parentheses

Comments: Temperature is expressed as a smooth mathematical function $T(z)$ with continuous first derivative. In the transition zone between homosphere and heterosphere (90–115 km) a combination of molecular and eddy diffusion coefficients is used to model vertical transport of individual species. Above 115 km eddy diffusion is negligible and molecular diffusion proceeds in a gravitational field $g = g_0/(1 + z/r_0)^2$, weakening with increasing altitude z, where r_0 is Earth's mean radius. Air composition is modeled to fit data from mass spectrometer, UV extinction, and satellite drag observations (N_2, O_2, O, Ar). As the species become separated by diffusion, the molar mass M changes with altitude and so does the pressure scale height $H_p = R_g T/gM$.

References

Banks, P.M., C. Kockarts, *Aeronomy (Part B, Appendix)* (Academic Press, New York, 1973)

Committee on Extension of US Standard Atmosphere (COESA), *US Standard Atmosphere 1976*, Washington, DC (1976)

Table 9.3a Thermosphere model for 750 K thermopause: Temperature T, pressure p, density ρ, total number concentration n, molar mass M, pressure scale height H_p and number concentrations of N_2, O_2, O, He, H as a function of altitude[a]

z (km)	T (K)	p (Pa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)	$n(N_2)$ (m^{-3})	$n(O_2)$ (m^{-3})	n(O) (m^{-3})	n(He) (m^{-3})	n(H) (m^{-3})
120	323.6	2.41 (−3)	2.34 (−8)	5.40 (17)	26.1	10.9	4.00 (17)	4.00 (16)	10.0 (16)	2.00 (13)	4.28 (12)
130	418.8	1.10 (−3)	7.95 (−9)	1.90 (17)	25.3	14.6	1.31 (17)	1.16 (16)	4.73 (16)	1.51 (13)	2.88 (12)
140	504.6	5.96 (−4)	3.48 (−9)	8.56 (16)	24.5	18.3	5.47 (16)	4.38 (15)	2.65 (16)	1.22 (13)	2.27 (12)
150	573.5	3.60 (−4)	1.79 (−9)	4.55 (16)	23.8	21.4	2.68 (16)	1.98 (15)	1.67 (16)	1.03 (13)	1.94 (12)
160	624.2	2.32 (−4)	1.03 (−9)	2.70 (16)	23.1	24.1	1.46 (16)	9.98 (14)	1.14 (16)	9.11 (12)	1.75 (12)
170	660.2	1.56 (−4)	6.38 (−10)	1.71 (16)	22.4	26.3	8.46 (15)	5.40 (14)	8.13 (15)	8.20 (12)	1.62 (12)
180	685.6	1.08 (−4)	4.14 (−10)	1.14 (16)	21.8	28.2	5.12 (15)	3.06 (16)	6.01 (15)	7.50 (12)	1.54 (12)
190	703.5	7.68 (−5)	2.78 (−10)	7.91 (15)	21.2	29.9	3.19 (15)	1.79 (14)	4.53 (15)	6.92 (12)	1.47 (12)
200	716.2	5.53 (−5)	1.92 (−10)	5.60 (15)	20.6	31.3	2.02 (15)	1.06 (14)	3.47 (15)	6.43 (12)	1.42 (12)
210	725.2	4.05 (−5)	1.35 (−10)	4.05 (15)	20.1	32.7	1.30 (15)	6.43 (13)	2.68 (15)	6.00 (12)	1.38 (12)
220	731.6	3.00 (−5)	9.66 (−11)	2.97 (15)	19.6	33.9	8.43 (14)	3.93 (13)	2.08 (15)	5.62 (12)	1.35 (12)
230	736.3	2.24 (−5)	7.02 (−11)	2.21 (15)	19.1	35.0	5.50 (14)	2.41 (13)	1.63 (15)	5.27 (12)	1.32 (12)
240	739.7	1.69 (−5)	5.16 (−11)	1.66 (15)	18.7	36.1	3.61 (14)	1.49 (13)	1.28 (15)	4.95 (12)	1.29 (12)
250	742.2	1.29 (−5)	3.83 (−11)	1.26 (15)	18.3	37.1	2.38 (14)	9.29 (12)	1.01 (15)	4.66 (12)	1.27 (12)
260	744.1	9.87 (−6)	2.87 (−11)	9.63 (14)	18.0	38.0	1.58 (14)	5.79 (12)	7.94 (14)	4.38 (12)	1.25 (12)
270	745.4	7.63 (−6)	2.17 (−11)	7.41 (14)	17.7	38.8	1.05 (14)	3.63 (12)	6.27 (14)	4.13 (12)	1.23 (12)
280	746.5	5.91 (−6)	1.66 (−11)	5.73 (14)	17.4	39.6	6.95 (13)	2.27 (12)	4.97 (14)	3.89 (12)	1.21 (12)
290	747.3	4.60 (−6)	1.27 (−11)	4.46 (14)	17.2	40.4	4.63 (13)	1.43 (12)	3.94 (14)	3.67 (12)	1.19 (12)
300	747.9	3.60 (−6)	9.81 (−12)	3.49 (14)	16.9	41.1	3.09 (13)	9.02 (11)	3.12 (14)	3.46 (12)	1.17 (12)
320	748.7	2.23 (−6)	5.92 (−12)	2.16 (14)	16.5	42.3	1.39 (13)	3.60 (11)	1.97 (14)	3.09 (12)	1.13 (12)
340	749.2	1.40 (−6)	3.64 (−12)	1.35 (14)	16.2	43.5	6.24 (12)	1.45 (11)	1.25 (14)	2.75 (12)	1.10 (12)
360	749.5	8.88 (−7)	2.26 (−12)	8.59 (13)	15.9	44.7	2.83 (12)	5.85 (10)	7.95 (13)	2.46 (12)	1.07 (12)
380	749.7	5.72 (−7)	1.42 (−12)	5.52 (13)	15.5	46.0	1.29 (12)	2.38 (10)	5.07 (13)	2.20 (12)	1.04 (12)

400	749.8	3.72 (−7)	9.04 (−13)	3.60 (13)	15.1	47.5	5.89 (11)	9.75 (9)	3.24 (13)	1.96 (12)	1.01 (12)
450	749.9	1.37 (−7)	3.01 (−13)	1.33 (13)	13.7	53.3	8.51 (10)	1.07 (9)	1.07 (13)	1.49 (12)	9.42 (11)
500	749.9	5.84 (−8)	1.06 (−13)	5.64 (12)	11.3	65.6	1.27 (10)	1.21 (7)	3.61 (12)	1.13 (12)	8.80 (11)
550	750.0	3.03 (−8)	4.00 (−14)	2.93 (12)	8.2	91.0	1.93 (9)	1.41 (7)	1.24 (12)	8.67 (11)	8.22 (11)
600	750.0	1.93 (−8)	1.71 (−14)	1.86 (12)	5.5	137.5	3.04 (8)	1.71 (6)	4.29 (11)	6.65 (11)	7.69 (11)
650	750.0	1.42 (−8)	8.63 (−15)	1.38 (12)	3.8	205.4	4.90 (7)	2.12 (5)	1.51 (11)	5.13 (11)	7.20 (11)
700	750.0	1.17 (−8)	5.20 (−15)	1.13 (12)	2.8	281.1	8.10 (6)		5.41 (10)	3.96 (11)	6.75 (11)
750	750.0	9.95 (−9)	3.63 (−15)	9.61 (11)	2.3	348.9	1.37 (6)		1.96 (4)	3.08 (11)	6.33 (11)
800	750.0	8.71 (−9)	2.78 (−15)	8.42 (11)	2.0	404.4	2.39 (5)		7.23 (10)	2.40 (11)	5.95 (11)
900	750.0	6.97 (−9)	1.88 (−15)	6.74 (11)	1.7	491.4			1.02 (9)	1.47 (11)	5.26 (11)
1,000	750.0	5.77 (−9)	1.39 (−15)	5.58 (11)	1.5	566.3			1.52 (8)	9.12 (10)	4.66 (11)

[a]Powers of ten are shown in parentheses; Source: Banks and Kockarts (1973), slightly condensed

Table 9.3b Thermosphere model for 1,000 K thermopause: Temperature T, pressure p, density ρ, total number concentration n, molar mass M, pressure scale height H_p and number concentrations of N_2, O_2, O, He, H as a function of altitude[a]

z (km)	T (K)	p* (Pa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)	$n(N_2)$ (m^{-3})	$n(O_2)$ (m^{-3})	n(O) (m^{-3})	n(He) (m^{-3})	n(H) (m^{-3})
120	323.6	2.41 (−3)	2.34 (−8)	5.40 (17)	26.1	10.9	4.00 (17)	4.00 (16)	10.0 (16)	2.00 (13)	2.61 (12)
130	472.7	1.15 (−3)	7.42 (−9)	1.77 (17)	25.3	16.4	1.23 (17)	1.09 (16)	4.32 (16)	1.41 (13)	1.22 (12)
140	596.4	6.80 (−4)	3.38 (−9)	8.25 (16)	24.7	21.4	5.37 (16)	4.40 (15)	2.44 (16)	1.12 (13)	7.53 (11)
150	692.5	4.44 (−4)	1.86 (−9)	4.64 (16)	24.1	25.5	2.84 (16)	2.17 (15)	1.59 (16)	9.53 (12)	5.41 (11)
160	765.2	3.08 (−4)	1.14 (−9)	2.91 (16)	23.5	29.0	1.67 (16)	1.20 (15)	1.13 (16)	8.42 (12)	4.25 (11)
170	819.8	2.21 (−4)	7.48 (−10)	1.96 (16)	23.0	31.8	1.05 (16)	7.12 (14)	8.38 (15)	7.63 (12)	3.54 (11)
180	861.0	1.64 (−4)	5.15 (−10)	1.38 (16)	22.5	34.3	6.88 (15)	4.43 (14)	6.45 (15)	7.02 (12)	3.07 (11)
190	892.2	1.23 (−4)	3.67 (−10)	1.00 (16)	22.0	36.4	4.66 (15)	2.85 (14)	5.08 (15)	6.52 (12)	2.74 (11)
200	915.9	9.45 (−5)	2.68 (−10)	7.48 (15)	21.6	38.3	3.22 (15)	1.87 (14)	4.07 (15)	6.11 (12)	2.50 (11)
210	934.0	2.32 (−5)	1.99 (−10)	5.68 (15)	21.1	40.0	2.26 (15)	1.25 (14)	3.29 (15)	5.75 (12)	2.32 (11)
220	948.0	5.73 (−5)	1.50 (−10)	4.38 (15)	20.7	41.6	1.60 (15)	8.48 (13)	2.69 (15)	5.44 (12)	2.18 (11)
230	958.8	4.53 (−5)	1.15 (−10)	3.42 (15)	20.3	43.0	1.15 (15)	5.80 (13)	2.21 (15)	5.16 (12)	2.07 (11)
240	967.2	3.60 (−5)	8.91 (−11)	2.70 (15)	19.9	44.4	8.26 (14)	3.99 (13)	1.83 (15)	4.90 (12)	1.98 (11)
250	973.7	2.88 (−5)	6.96 (−11)	2.15 (15)	19.5	45.7	5.99 (14)	2.77 (13)	1.52 (15)	4.67 (12)	1.90 (11)
260	978.9	2.32 (−5)	5.48 (−11)	1.72 (15)	19.2	46.8	4.36 (14)	1.93(13)	1.26 (15)	4.45 (12)	1.84 (11)
270	983.0	1.88 (−5)	4.35 (−11)	1.39 (15)	18.9	48.0	3.18 (14)	1.35 (13)	1.05 (15)	4.24 (12)	1.79 (11)
280	986.2	1.53 (−5)	3.47 (−11)	1.13 (15)	18.6	49.0	2.33 (14)	9.43 (12)	8.79 (14)	4.05 (12)	1.74 (11)
290	988.8	1.25 (−5)	2.79 (−11)	9.18 (14)	18.3	50.0	1.71 (14)	6.63 (12)	7.36 (14)	3.87 (12)	1.70 (11)
300	990.8	1.03 (−5)	2.25 (−11)	7.52 (14)	18.0	51.0	1.26 (14)	4.67 (12)	6.17 (14)	3.70 (12)	1.67 (11)
320	993.9	7.00 (−6)	1.22 (−11)	4.22 (14)	17.6	52.8	6.85 (13)	2.33 (12)	4.36 (14)	3,39 (12)	1.61 (11)
340	995.9	4.81 (−6)	1.00 (−11)	3.51 (14)	17.2	54.3	3.76 (13)	1.17 (12)	3.09 (14)	3.11 (12)	1.56 (11)
360	997.2	3.35 (−6)	6.84 (−12)	2.44 (14)	16.9	55.8	2.07 (13)	5.93 (11)	2.19 (14)	2.85 (12)	1.51 (11)
380	998.1	2.35 (−6)	4.72 (−12)	1.71 (14)	16.6	57.1	1.14 (13)	3.01 (11)	1.56 (14)	2.62 (12)	1.47 (11)
400	998.7	1.66 (−6)	3.29 (−12)	1.21 (14)	16.4	58.3	6.36 (12)	1.54 (11)	1.12 (14)	2.41 (12)	1.44 (11)

450	999.6	7.21 (−7)	1.38 (−12)	5.23 (13)	15.9	61.2	1.49 (12)	2.93 (10)	4.87 (13)	1.95 (12)	1.36 (11)
500	999.9	3.25 (−7)	5.99 (−13)	2.36 (13)	15.3	64.4	3.56 (11)	5.72 (9)	2.15 (13)	1.59 (12)	1.29 (11)
550	1000.1	1.53 (−7)	2.68 (−13)	1.11 (13)	14.5	68.9	8.70 (10)	1.14 (9)	9.61 (12)	1.30 (12)	1.22 (11)
600	1000.1	7.67 (−8)	1.24 (−13)	5.56 (12)	13.4	75.6	2.17 (10)	2.34 (8)	4.35 (12)	1.07 (12)	1.16 (11)
650	1000.2	4.12 (−8)	5.91 (−14)	2.98 (12)	11.9	86.3	5.53 (9)	4.89 (7)	1.99 (12)	8.78 (11)	1.11 (11)
700	1000.2	2.41 (−8)	2.95 (−14)	1.75 (12)	10.2	102.9	1.43 (9)	1.05 (7)	9.21 (11)	7.24 (11)	1.05 (11)
750	1000.2	1.56 (−8)	1.56 (−14)	1.13 (12)	8.3	127.4	3.79 (8)	2.29 (6)	4.31 (11)	5.99 (11)	1.00 (11)
800	1000.2	1.10 (−8)	8.87 (−15)	7.96 (11)	6.7	160.0	1.02 (8)	5.12 (5)	2.04 (11)	4.96 (11)	9.57 (10)
900	1000.2	6.60 (−9)	3.68 (−15)	4.78 (11)	4.6	238.4	7.84 (6)		4.69 (10)	3.44 (11)	8.73 (10)
1,000	1000.2	4.57 (−9)	2.03 (−15)	3.32 (11)	3.7	307.7	6.44 (5)		1.13 (10)	2.41 (11)	7.98 (10)

[a]Powers of ten are shown in parentheses; Source: Banks and Kockarts (1973), slightly condensed

Table 9.3c Thermosphere model for 1,250 K thermopause: Temperature T, pressure p, density ρ, total number concentration n, molar mass M, pressure scale height H_p and number concentrations of N_2, O_2, O, He, H as a function of altitude[a]

z (km)	T (K)	p (Pa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)	$n(N_2)$ (m^{-3})	$n(O_2)$ (m^{-3})	n(O) (m^{-3})	n(He) (m^{-3})	n(H) (m^{-3})
120	323.6	2.41 (−3)	2.34 (−8)	5.40 (17)	26.1	10.9	4.00 (17)	4.00 (16)	10.0 (16)	2.00 (13)	2.61 (12)
130	523.3	1.20 (−3)	7.01 (−9)	1.66 (17)	25.4	18.2	1.16 (17)	1.04 (16)	4.01 (16)	1.33 (13)	1.01 (12)
140	677.5	7.48 (−4)	3.30 (−9)	8.01 (16)	24.8	24.2	5.28 (16)	4.40 (15)	2.29 (16)	1.05 (13)	5.90 (11)
150	796.5	5.14 (−4)	1.89 (−9)	4.69 (16)	24.3	29.1	2.93 (16)	2.29 (15)	1.53 (16)	8.96 (12)	3.99 (11)
160	888.4	3.73 (−4)	1.21 (−9)	3.05 (16)	23.8	33.2	1.81 (16)	1.34 (15)	1.11 (16)	7.94 (12)	2.94 (11)
170	959.9	2.81 (−4)	8.23 (−10)	2.12 (16)	23.4	36.7	1.19 (16)	8.43 (14)	8.43 (15)	7.21 (12)	2.28 (11)
180	1015.9	2.16 (−4)	5.88 (−10)	1.54 (16)	23.0	39.7	8.21 (15)	5.55 (14)	6.65 (15)	6.65 (12)	1.85 (11)
190	1060.2	1.69 (−4)	4.34 (−10)	1.16 (16)	22.6	42.2	5.83 (15)	3.77 (14)	5.37 (15)	6.20 (12)	1.54 (11)
200	1095.5	1.35 (−4)	3.28 (−10)	8.90 (15)	22.2	44.6	4.23 (15)	2.63 (14)	4.41 (15)	5.83 (12)	1.31 (11)
210	1123.6	1.08 (−4)	2.52 (−10)	6.97 (15)	21.8	46.6	3.12 (15)	1.86 (14)	3.66 (15)	5.52 (12)	1.14 (11)
220	1146.3	8.76 (−5)	1.97 (−10)	5.54 (15)	21.4	48.5	2.33 (15)	1.34 (14)	3.07 (15)	5.24 (12)	1.01 (11)
230	1164.6	7.16 (−5)	1.56 (−10)	4.46 (15)	21.1	50.3	1.76 (15)	9.71 (13)	2.60 (15)	5.00 (12)	9.05 (10)
240	1179.4	5.89 (−5)	1.24 (−10)	3.62 (15)	20.7	52.0	1.33 (15)	7.11 (13)	2.21 (15)	4.78 (12)	8.22 (10)
250	1191.5	4.87 (−5)	1.00 (−10)	2.96 (15)	20.4	53.4	1.02 (15)	5.24 (13)	1.89 (15)	4.57 (12)	7.54 (10)
260	1201.3	4.05 (−5)	8.15 (−11)	2.44 (15)	20.1	54.9	7.84 (14)	3.88 (13)	1.62 (15)	4.39 (12)	6.99 (10)
270	1209.4	3.39 (−5)	6.66 (−11)	2.03 (15)	19.8	56.3	6.05 (14)	2.89 (13)	1.39 (15)	4.21 (12)	6.53 (10)
280	1216.1	2.84 (−5)	5.48 (−11)	1.69 (15)	19.5	57.6	4.69 (14)	2.16 (13)	1.20 (15)	4.05 (12)	6.14 (10)
290	1221.6	2.39 (−5)	4.53 (−11)	1.42 (15)	19.2	58.8	3.64 (14)	1.62 (13)	1.04 (15)	3.90 (12)	5.82 (10)
300	1226.2	2.03 (−5)	3.76 (−11)	1.20 (15)	19.0	60.1	2.83 (14)	1.22 (13)	8.96 (14)	3.76 (12)	5.54 (10)
320	1233.1	1.72 (−5)	2.63 (−11)	8.58 (14)	18.5	62.3	1.73 (14)	6.93 (12)	6.74 (14)	3.49 (12)	5.10 (10)
340	1238.0	1.19 (−5)	1.87 (−11)	6.23 (14)	18.1	64.4	1.06 (14)	3.97 (12)	5.09 (14)	3.25 (12)	4.77 (10)
360	1241.5	8.76 (−6)	1.35 (−11)	4.58 (14)	17.7	66.3	6.57 (13)	2.29 (12)	3.87 (14)	3.03 (12)	4.51 (10)
380	1244.0	6.51 (−6)	9.80 (−12)	3.39 (14)	17.4	68.0	4.08 (13)	1.33 (12)	2.96 (14)	2.83 (12)	4.30 (10)
400	1245.9	4.87 (−6)	7.20 (−12)	2.53 (14)	17.1	69.6	2.54 (13)	7.76 (11)	2.24 (14)	2.64 (12)	4.14 (10)

450	1248.6	2.41 (−6)	3.46 (−12)	1.26 (14)	16.6	73.3	7.94 (12)	2.05 (11)	1.15 (14)	2.23 (12)	3.82 (10)
500	1249.9	1.24 (−6)	1.72 (−12)	6.44 (13)	16.1	76.4	2.53 (12)	5.54 (10)	5.99 (13)	1.90 (12)	3.60 (10)
550	1250.6	5.85 (−7)	8.84 (−13)	3.39 (13)	15.7	79.6	8.18 (11)	1.53 (10)	3.14 (13)	1.61 (12)	3.42 (10)
600	1250.9	3.17 (−7)	4.65 (−13)	1.83 (13)	15.3	83.3	2.70 (11)	4.29 (9)	1.67 (13)	1.38 (12)	3.27 (10)
650	1251.1	1.76 (−7)	2.49 (−13)	1.02 (13)	14.7	87.8	9.03 (10)	1.23 (9)	8.92 (12)	1.18 (12)	3.13 (10)
700	1251.2	1.01 (−7)	1.36 (−13)	5.89 (12)	13.9	93.8	3.07 (10)	3.59 (8)	4.82 (12)	1.01 (12)	3.00 (10)
750	1251.2	6.09 (−8)	7.60 (−14)	3.53 (12)	13.0	102.2	1.06 (10)	1.06 (8)	2.62 (12)	8.66 (11)	2.89 (10)
800	1251.2	3.83 (−8)	4.35 (−14)	2.22 (12)	11.8	129.9	3.72 (9)	3.21 (7)	1.44 (12)	7.46 (11)	2.78 (10)
900	1251.3	1.77 (−8)	1.56 (−14)	1.03 (12)	9.1	151.1	4.77 (8)	3.07 (6)	4.46 (11)	5.56 (11)	2.48 (10)
1,000	1251.3	1.01 (−8)	6.60 (−15)	5.84 (11)	6.8	208.5	6.47 (7)	3.14 (5)	1.42 (11)	4.18 (11)	2.40 (10)

[a]Powers of ten are shown in parentheses; Source: Banks and Kockarts (1973), slightly condensed

Table 9.3d Thermosphere model for 1,500 K thermopause: Temperature T, pressure p, density ρ, total number concentration n, molar mass M, pressure scale height H_p and number concentrations of N_2, O_2, O, He, H as a function of altitude[a]

z (km)	T (K)	p (Pa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)	$n(N_2)$ (m^{-3})	$n(O_2)$ (m^{-3})	n(O) (m^{-3})	n(He) (m^{-3})	n(H) (m^{-3})
120	323.6	2.41 (−3)	2.34 (−8)	5.40 (17)	26.1	10.9	4.00 (17)	4.00 (16)	10.0 (16)	2.00 (13)	2.37 (12)
130	527.9	1.20 (−3)	6.95 (−9)	1.65 (17)	25.4	18.4	1.15 (17)	1.03 (16)	3.98 (16)	1.33 (13)	9.73 (11)
140	702.1	7.57 (−4)	3.22 (−9)	7.81 (16)	24.8	25.1	5.16 (16)	4.30 (15)	2.23 (16)	1.03 (13)	5.53 (11)
150	844.9	5.29 (−4)	1.83 (−9)	4.54 (16)	24.3	30.9	2.85 (16)	2.24 (15)	1.47 (16)	8.67 (12)	3.66 (11)
160	959.8	3.92 (−4)	1.17 (−9)	2.96 (16)	23.9	35.8	1.77 (16)	1.33 (15)	1.06 (16)	7.62 (12)	2.64 (11)
170	1052.3	3.01 (−4)	8.09 (−10)	2.08 (16)	23.5	40.0	1.18 (16)	8.47 (14)	8.07 (15)	6.89 (12)	2.01 (11)
180	1127.2	2.37 (−4)	5.85 (−10)	1.53 (16)	23.1	43.7	8.29 (15)	5.70 (14)	6.39 (15)	6.34 (12)	1.60 (11)
190	1188.3	1.91 (−4)	4.39 (−10)	1.16 (16)	22.8	47.0	6.01 (15)	3.97 (14)	5.20 (15)	5.90 (12)	1.30 (11)
200	1238.3	1.55 (−4)	3.37 (−10)	9.06 (15)	22.4	49.9	4.46 (15)	2.84 (14)	4.31 (15)	5.54 (12)	1.09 (11)
210	1279.6	1.27 (−4)	2.64 (−10)	7.22 (15)	22.1	52.5	3.38 (15)	2.08 (14)	3.62 (15)	5.25 (12)	9.24 (10)
220	1313.8	1.06 (−4)	2.11 (−10)	5.83 (15)	21.7	54.8	2.59 (15)	1.54 (14)	3.08 (15)	4.99 (12)	7.97 (10)
230	1342.2	8.84 (−5)	1.70 (−10)	4.77 (15)	21.4	57.0	2.01 (15)	1.16 (14)	2.64 (15)	4.76 (12)	6.95 (10)
240	1366.0	7.44 (−5)	1.39 (−10)	3.95 (15)	21.1	59.0	1.58 (15)	8.78 (13)	2.28 (15)	4.56 (12)	6.13 (10)
250	1386.0	6.31 (−5)	1.14 (−10)	3.29 (15)	20.8	60.9	1.24 (15)	6.71 (13)	1.98 (15)	4.38 (12)	5.46 (10)
260	1402.8	5.36 (−5)	9.45 (−11)	2.77 (15)	20.6	62.7	9.87 (14)	5.16 (13)	1.73 (15)	4.21 (12)	4.91 (10)
270	1416.9	4.57 (−5)	7.89 (−11)	2.34 (15)	20.3	64.3	7.88 (14)	3.99 (13)	1.51 (15)	4.06 (12)	4.45 (10)
280	1428.9	3.93 (−5)	6.62 (−11)	1.99 (15)	20.0	65.9	6.31 (14)	3.10 (13)	1.33 (15)	3.92 (12)	4.07 (10)
290	1439.1	3.39 (−5)	5.59 (−11)	1.70 (15)	19.8	67.4	5.08 (14)	2.42 (13)	1.17 (15)	3.78 (12)	3.74 (10)
300	1447.8	2.92 (−5)	4.74 (−11)	1.46 (15)	19.5	68.9	4.09 (14)	1.90 (13)	1.03 (15)	3.66 (12)	3.46 (10)
320	1461.6	2.20 (−5)	3.45 (−11)	1.09 (15)	19.1	71.6	2.68 (14)	1.17 (13)	8.06 (14)	3,.43 (12)	3.01 (10)
340	1471.7	1.67 (−5)	2.55 (−11)	8.22 (14)	18.7	74.1	1.77 (14)	7.31 (12)	6.34 (14)	3.22 (12)	2.68 (10)
360	1479.3	1.28 (−5)	1.91 (−11)	6.27 (14)	18.3	76.4	1.18 (14)	4.60 (12)	5.01 (14)	3.03 (12)	2.42 (10)
380	1485.0	9.89 (−6)	1.44 (−11)	4.83 (14)	18.0	78.6	7.91 (13)	2.91 (12)	3.98 (14)	2.86 (12)	2.22 (10)
400	1489.3	7.69 (−6)	1.10 (−11)	3.74 (14)	17.7	80.6	5.31 (13)	1.85 (12)	3.17 (14)	2.69 (12)	2.06 (10)

450	1496.2	4.21 (−6)	5.78 (−12)	2.04 (14)	17.1	85.1	2.00 (13)	6.06 (11)	1.81 (14)	2.34 (12)	1.79 (10)
500	1499.9	2.37 (−6)	3.16 (−12)	1.15 (14)	16.6	89.0	7.69 (12)	2.03 (11)	1.05 (14)	2.04 (12)	1.62 (10)
550	1501.9	1.38 (−6)	1.78 (−12)	6.60 (13)	16.2	92.6	3.01 (12)	6.94 (10)	6.11 (13)	1.78 (12)	1.51 (10)
600	1503.1	8.05 (−7)	1.02 (−12)	3.88 (13)	15.9	96.0	1.19 (12)	2.41 (10)	3.60 (13)	1.56 (12)	1.42 (10)
650	1503.7	4.83 (−7)	6.00 (−13)	2.33 (13)	15.5	99.7	4.80 (11)	8.52 (9)	2.14 (13)	1.37 (12)	1.36 (10)
700	1504.1	2.96 (−7)	3.58 (−13)	1.42 (13)	15.1	103.8	1.96 (11)	3.05 (9)	1.28 (13)	1.20 (12)	1.30 (10)
750	1504.4	1.84 (−7)	2.16 (−13)	8.89 (12)	14.7	108.7	8.07 (10)	1.11 (9)	7.73 (12)	1.06 (12)	1.25 (10)
800	1504.5	1.18 (−7)	1.33 (−13)	5.68 (12)	14.1	114.9	3.38 (10)	4.11 (8)	4.70 (12)	9.36 (11)	1.21 (10)
900	1504.7	5.24 (−8)	5.22 (−14)	2.52 (12)	12.5	133.2	6.12 (9)	5.83 (7)	1.77 (12)	7.33 (11)	1.13 (10)
1,000	1504.7	2.65 (−8)	2.21 (−14)	1.28 (12)	10.5	163.5	1.16 (9)	8.74 (6)	6.86 (11)	5.78 (11)	1.07 (10)

[a]Powers of ten are shown in parentheses; Source: Banks and Kockarts (1973), slightly condensed

Table 9.3e Thermosphere model for 1,750 K thermopause: Temperature T, pressure p, density ρ, total number concentration n, molar mass M, pressure scale height H_p and number concentrations of N_2, O_2, O, He, H as a function of altitude[a]

z (km)	T (K)	p (Pa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)	$n(N_2)$ (m^{-3})	$n(O_2)$ (m^{-3})	n(O) (m^{-3})	n(He) (m^{-3})	n(H) (m^{-3})
120	323.6	2.41 (−3)	2.34 (−8)	5.40 (17)	26.1	10.9	4.00 (17)	4.00 (16)	10.0 (16)	2.00 (13)	2.37 (12)
130	571.3	1.24 (−3)	6.64 (−9)	1.57 (17)	25.4	19.9	1.10 (17)	9.92 (15)	3.75 (16)	1.27 (13)	9.52 (11)
140	769.8	8.12 (−4)	3.16 (−9)	7.64 (16)	24.9	27.3	5.09 (16)	4.29 (15)	2.12 (16)	9.85 (12)	5.50 (11)
150	930.0	5.85 (−4)	1.85 (−9)	4.56 (16)	24.5	33.8	2.90 (16)	2.32 (15)	1.42 (16)	8.31 (12)	3.70 (11)
160	1059.6	4.45 (−4)	1.22 (−9)	3.04 (16)	24.1	39.2	1.86 (16)	1.42 (15)	1.04 (16)	7.32 (12)	2.70 (11)
170	1165.5	3.49 (−4)	8.56 (−10)	2.17 (16)	23.7	43.9	1.27 (16)	9.36 (14)	8.06 (15)	6.63 (12)	2.07 (11)
180	1252.8	2.81 (−4)	6.32 (−10)	1.63 (16)	23.4	48.0	9.16 (15)	6.48 (14)	6.47 (15)	6.11 (12)	1.65 (11)
190	1325.4	2.30 (−4)	4.82 (−10)	1.26 (16)	23.1	51.7	6.80 (15)	4.64 (14)	5.32 (15)	5.70 (12)	1.35 (11)
200	1386.1	1.91 (−4)	3.77 (−10)	9.98 (15)	22.8	54.9	5.17 (15)	3.42 (14)	4.47 (15)	5.37 (12)	1.12 (11)
210	1437.3	1.60 (−4)	3.01 (−10)	8.06 (15)	22.5	57.9	4.00 (15)	2.57 (14)	3.80 (15)	5.08 (12)	9.49 (10)
220	1480.6	1.35 (−4)	2.11 (−10)	5.83 (15)	22.2	60.6	3.14 (15)	1.96 (14)	3.27 (15)	4.84 (12)	8.14 (10)
230	1517.4	1.15 (−4)	1.99 (−10)	5.49 (15)	21.9	63.1	2.50 (15)	1.51 (14)	2.84 (15)	4.63 (12)	7.05 (10)
240	1548.8	9.84 (−5)	1.65 (−10)	4.60 (15)	21.6	65.4	2.00 (15)	1.18 (14)	2.18 (15)	4.28 (12)	5.43 (10)
250	1575.7	8.47 (−5)	1.38 (−10)	3.89 (15)	21.4	67.6	1.62 (15)	9.24 (13)	1.98 (15)	4.38 (12)	5.46 (10)
260	1598.8	7.32 (−5)	1.16 (−10)	3.32 (15)	21.1	69.6	1.32 (15)	7.31 (13)	1.92 (15)	4.12 (12)	4.83 (10)
270	1618.8	6.35 (−5)	9.84 (−11)	2.84 (15)	20.9	71.5	1.08 (15)	5.82 (13)	1.70 (15)	3.98 (12)	4.32 (10)
280	1635.9	5.53 (−5)	8.39 (−11)	2.45 (15)	20.6	73.3	8.84 (14)	4.65 (13)	1.52 (15)	3.85 (12)	3.88 (10)
290	1650.8	4.84 (−5)	7.18 (−11)	2.12 (15)	20.4	75.0	7.29 (14)	3.73 (13)	1.35 (15)	3.73 (12)	3.51 (10)
300	1663.7	4.24 (−5)	6.18 (−11)	1.85 (15)	20.2	76.7	6.03 (14)	3.01 (13)	1.21 (15)	3.62 (12)	3.20 (10)
320	1684.7	3.28 (−5)	4.63 (−11)	1.41 (15)	19.7	79.8	4.16 (14)	1.97 (13)	9.73 (14)	3.41 (12)	2.68 (10)
340	1700.8	2.57 (−5)	3.51 (−11)	1.09 (15)	19.3	82.7	2.90 (14)	1.31 (13)	7.88 (14)	3.22 (12)	2.29 (10)
360	1713.1	2.03 (−5)	2.70 (−11)	8.57 (14)	19.0	85.5	2.03 (14)	8.72 (12)	6.42 (14)	3.05 (12)	1.99 (10)
380	1722.7	1.61 (−5)	2.09 (−11)	6.77 (14)	18.6	88.0	1.43 (14)	5.86 (12)	5.24 (14)	2.90 (12)	1.76 (10)
400	1730.1	1.29 (−5)	1.64 (−11)	5.38 (14)	18.3	90.5	1.02 (14)	3.96 (12)	4.30 (14)	2.75 (12)	1.57 (10)

450	1742.6	7.51 (−6)	9.17 (−12)	3.13 (14)	17.7	95.9	4.38 (13)	1.51 (12)	2.65 (14)	2.43 (12)	1.25 (10)
500	1749.8	4.52 (−6)	5.33 (−12)	1.87 (14)	17.1	100.7	1.92 (13)	5.91 (11)	1.65 (14)	2.16 (12)	1.05 (10)
550	1754.0	2.79 (−6)	3.19 (−12)	1.15 (14)	16.7	104.9	8.59 (12)	2.35 (11)	1.04 (14)	1.92 (12)	9.24 (9)
600	1756.5	1.75 (−6)	1.96 (−12)	7.19 (13)	16.4	108.9	3.89 (12)	9.52 (10)	6.62 (13)	1.71 (12)	8.42 (9)
650	1758.1	1.11 (−6)	1.22 (−12)	4.58 (13)	16.1	112.6	1.78 (12)	3.90 (10)	4.24 (13)	1.53 (12)	7.82 (9)
700	1759.1	7.17 (−7)	7.74 (−13)	2.96 (13)	15.8	116.4	8.72 (11)	1.62 (10)	2.73 (13)	1.37 (12)	7.38 (9)
750	1759.8	4.71 (−7)	4.98 (−13)	1.94 (13)	15.5	120.4	3.88 (11)	6.84 (9)	1.77 (13)	1.23 (12)	7.04 (9)
800	1760.2	3.13 (−7)	3.24 (−13)	1.29 (13)	15.1	125.0	1.84 (11)	2.92 (9)	1.16 (13)	1.11 (12)	6.76 (9)
900	1760.7	1.45 (−7)	1.42 (−13)	5.98 (12)	14.3	136.3	4.28 (10)	5.52 (8)	5.03 (12)	8.99 (11)	6.31 (9)
1,000	1760.9	7.25 (−8)	6.47 (−14)	2.99 (12)	13.1	153.0	1.04 (10)	1.09 (8)	2.24 (12)	7.34 (11)	5.95 (9)

[a]Powers of ten are shown in parentheses; Source: Banks and Kockarts (1973), slightly condensed

Table 9.3f Thermosphere model for 2,000 K thermopause: Temperature T, pressure p, density ρ, total number concentration n, molar mass M, pressure scale height H_p and number concentrations of N_2, O_2, O, He, H as a function of altitude[a]

z (km)	T (K)	p (Pa)	ρ (kg m^{-3})	n (m^{-3})	M (g mol^{-1})	H_p (km)	$n(N_2)$ (m^{-3})	$n(O_2)$ (m^{-3})	n(O) (m^{-3})	n(He) (m^{-3})	n(H) (m^{-3})
120	323.6	2.41 (−3)	2.34 (−8)	5.40 (17)	26.1	10.9	4.00 (17)	4.00 (16)	10.0 (16)	2.00 (13)	2.37 (12)
130	590.9	1.26 (−3)	6.50 (−9)	1.54 (17)	25.4	20.5	1.08 (17)	9.74 (15)	3.65 (16)	1.24 (13)	9.44 (11)
140	807.9	8.35 (−4)	3.10 (−9)	7.49 (16)	24.9	28.7	5.01 (16)	4.24 (15)	2.06 (16)	9.60 (12)	5.48 (11)
150	985.5	6.12 (−4)	1.83 (−9)	4.50 (16)	24.5	35.7	2.89 (16)	2.32 (15)	1.38 (16)	8.07 (12)	3.70 (11)
160	1131.4	4.73 (−4)	1.21 (−9)	3.03 (16)	24.2	41.7	1.87 (16)	1.44 (15)	1.02 (16)	7.10 (12)	2.72 (11)
170	1252.4	3.77 (−4)	8.64 (−10)	2.18 (16)	23.8	47.0	1.30 (16)	9.64 (14)	7.89 (15)	6.42 (12)	2.10 (11)
180	1353.7	3.08 (−4)	6.44 (−10)	1.65 (16)	23.5	51.6	9.44 (15)	6.78 (14)	6.37 (15)	5.91 (12)	1.68 (11)
190	1439.2	2.56 (−4)	4.96 (−10)	1.29 (16)	23.2	55.7	7.10 (15)	4.94 (14)	5.27 (15)	5.52 (12)	1.38 (11)
200	1512.0	2.15 (−4)	3.92 (−10)	1.03 (16)	22.9	59.4	5.48 (15)	3.70 (14)	4.45 (15)	5.19 (12)	1.15 (11
210	1574.2	1.83 (−4)	3.16 (−10)	8.40 (15)	22.7	62.8	4.30 (15)	2.82 (14)	3.81 (15)	4.92 (12)	9.77 (10)
220	1627.6	1.56 (−4)	2.59 (−10)	6.96 (15)	22.4	65.9	3.43 (15)	2.19 (14)	3.30 (15)	4.69 (12)	8.40 (10)
230	1673.8	1.35 (−4)	2.15 (−10)	5.83 (15)	22.2	68.7	2.77 (15)	1.72 (14)	2.88 (15)	4.49 (12)	7.29 (10)
240	1713.8	1.17 (−4)	1.80 (−10)	4.94 (15)	21.9	71.4	2.26 (15)	1.37 (14)	2.54 (15)	4.31 (12)	6.38 (10)
250	1748.7	1.02 (−4)	1.52 (−10)	4.22 (15)	21.7	73.9	1.85 (15)	1.09 (14)	2.25 (15)	4.15 (12)	5.62 (10)
260	1779.0	8.91 (−5)	1.29 (−10)	3.63 (15)	21.4	76.2	1.53 (15)	8.83 (13)	2.00 (15)	4.00 (12)	4.99 (10)
270	1805.6	7.83 (−5)	1.11 (−10)	3.14 (15)	21.2	78.4	1.27 (15)	7.16 (13)	1.79 (15)	3.87 (12)	4.46 (10)
280	1828.9	6.91 (−5)	9.53 (−11)	2.73 (15)	21.0	80.5	1.06 (15)	5.84 (13)	1.61 (15)	3.75 (12)	4.00 (10)
290	1849.4	6.11 (−5)	8.25 (−11)	2.39 (15)	20.8	82.5	8.93 (14)	4.79 (13)	1.45 (15)	3.64 (12)	3.61 (10)
300	1867.5	5.41 (−5)	7.18 (−11)	2.10 (15)	20.6	84.4	7.52 (14)	3.94 (13)	1.31 (15)	3.53 (12)	3.27 (10)
320	1897.5	4.29 (−5)	5.49 (−11)	1.64 (15)	20.2	88.0	5.38 (14)	2.69 (13)	1.07 (15)	3.34 (12)	2.71 (10)
340	1921.1	3.44 (−5)	4.26 (−11)	1.30 (15)	19.8	91.3	3.89 (14)	1.86 (13)	8.85 (14)	3.17 (12)	2.29 (10)
360	1939.7	2.77 (−5)	3.34 (−11)	1.03 (15)	19.4	94.4	2.83 (14)	1.30 (13)	7.36 (14)	3.02 (12)	1.95 (10)
380	1954.6	2.25 (−5)	2.65 (−11)	8.34 (14)	19.1	97.3	2.08 (14)	9.11 (12)	6.14 (14)	2.88 (12)	1.69 (10)

400	1966.5	1.84 (−5)	2.11 (−11)	6.77 (14)	18.8	100.1	1.53 (14)	6.44 (12)	5.15 (14)	2.75 (12)	1.47 (10)
450	1987.1	1.13 (−5)	1.24 (−11)	4.13 (14)	18.1	106.4	7.27 (13)	2.75 (12)	3.35 (14)	2.46 (12)	1.10 (10)
500	1999.6	7.16 (−6)	7.59 (−12)	2.60 (14)	17.6	112.0	3.53 (13)	1.21 (12)	2.21 (14)	2.21 (12)	8.71 (9)
550	2007.4	4.63 (−6)	4.76 (−12)	1.67 (14)	17.2	117.1	1.74 (13)	5.38 (11)	1.47 (14)	1.99 (12)	7.23 (9)
600	2012.3	3.05 (−6)	3.06 (−12)	1.10 (14)	16.8	121.7	8.70 (12)	2.44 (11)	9.90 (13)	1.80 (12)	6.26 (9)
650	2015.6	2.04 (−6)	2.00 (−12)	7.32 (13)	16.5	126.0	4.40 (12)	1.12 (11)	6.70 (13)	1.63 (12)	5.58 (9)
700	2017.7	1.33 (−6)	1.33 (−12)	4.95 (13)	16.2	130.1	2.25 (12)	5.21 (10)	4.57 (13)	1.48 (12)	5.10 (9)
750	2019.2	9.44 (−7)	8.97 (−13)	3.39 (13)	15.9	134.2	1.17 (12)	2.45 (10)	3.13 (13)	1.35 (12)	4.75 (9)
800	2020.2	6.55 (−7)	6.11 (−13)	2.35 (13)	15.7	138.4	6.08 (11)	1.17 (10)	2.16 (13)	1.23 (12)	4.49 (9)
900	2021.4	3.25 (−7)	2.92 (−13)	1.16 (13)	15.1	147.7	1.71 (11)	2.73 (9)	1.04 (13)	1.03 (12)	4.11 (9)
1,000	2022.0	1.69 (−7)	1.45 (−13)	6.07 (12)	14.4	159.5	4.95 (10)	6.64 (8)	5.15 (12)	8.59 (11)	3.84 (9)

[a]Powers of ten are shown in parentheses; Source of data: Banks and Kockarts (1973), slightly condensed

9.3 Solar Radiation at Wavelengths Below 200 nm

Solar radiation in the far and extreme ultraviolet spectral regions is subject to variations with solar activity that are caused, both by the Sun's rotation (25 day at the solar equator, 35 day at the solar poles, 27 day average), and by the ~11 year sun spot cycle. Solar activity arises from the interaction of magnetic fields with the Sun's outer atmosphere. Thereby sites of activity are generated where photon emissions are either enhanced or depleted in comparison to the unperturbed solar atmosphere. Further sporadic perturbations are caused by solar flares, which affect mainly emissions in the X-ray region (~1,000 events per solar cycle). At wavelengths below about 200 nm the general character of the solar spectrum changes from a continuum with superimposed absorption features (such as Fraunhofer lines) to a much weaker continuum superimposed by emission lines; and the intensity decreases with decreasing wavelengths by more than four orders of magnitude (Tables 9.6 and 9.7 for solar cycles 21 and 22 below).

In the atmosphere of Earth, molecular oxygen absorbs radiation in the 120–175 nm wavelength range at altitudes above 100 km, and radiation between 175 and 200 nm in the mesosphere. Both, absorption at high altitudes and the dependence on solar activity make studies of solar radiation in the far ultraviolet spectral region quite demanding. Observations avoiding effects due to atmospheric absorption requires vehicles that can reach high altitudes. Since about 1960, both rockets and satellites have served as carriers of instruments designed to determine the spectral intensity distribution of solar radiation at short wavelengths. A further requirement arose to develop empirical models for estimating daily flux variations. Such models are based on a background at quiet solar conditions augmented by a wavelength-dependent contribution varying linearly with a proxy indicator such as the $F_{10.7}$cm radio emission (see Table 9.5). For overviews on existing measurements and models see Geophysical Monograph 141 (Pap et al. 2004). In the following, the wavelength unit Ångström (Å) has been retained when it was used to describe the original data (1 nm = 10 Å) (Table 9.4).

Table 9.4 Overview on solar EUV irradiance measurements from spacecraft[a]

Spacecraft/Instrument	λ Range (nm)	Δλ Resolution (nm)	Time period
SOLRAD-1-11	1–10	1	1960–1976
OSO-3-6/SES	2–40	0.1	1967–1970
OSO-3-6/EUVS	27–131	0.2	1967–1970
AEROS-A-B	20–104	1	1973–1975
AE-C-E/EUVS	14–185	0.2–1	1974–1981
AE-C-E/ESUM	22–122	1–30	1974–1981
GOES/XRS	0.1–0.8	1	1974–present
Nimbus-7/SBUV	160–400	1.1	1978–1987
SME	115–300	0.75	1981–1989
NOAA-9/SBUV[b]	160–405	1.1	1984–1998
NOAA-16/SBUV[b]	160–405	1.1	2000–present
San Marco/ASSI	30–400	1	1988
Yohkoh/SXT	0.2–3	3	1992–present
SOHO CELIAS/SEM	26–34	8	1996–present

(continued)

Table 9.4 (continued)

Spacecraft/Instrument	λ Range (nm)	Δλ Resolution (nm)	Time period
SNOE/SXP	0.2–20	4–7	1998–present
UARS/SOLSTICE	119–420	0.1–0.3	1991–present
UARS/SUSIM	115–410	0.15, 1.1, 5	1991–present

[a]Source: Pap et al. (2004)
[b]Since 1984 SBUV instruments were flown on NOAA operational weather satellites, launched in 1984, 1989, 1995, 2000

Acronyms:

Satellites: AE = Atmospheric Explorer; AEROS = Aeronomy Satellites; OSO = Orbiting Solar Observatory; GOES = Geostationary Operational Environmental Satellite; SME = Solar Mesospheric Explorer; SNOE = Student Nitric Oxide Explorer; SOHO = Solar and Heliospheric Observatory; SOLRAD = Solar Radiation Spacecraft; UARS = Upper Atmosphere Research Satellite.

Instrumentation: ASSI = Airglow Solar Spectrometer Instrument; CELIAS = Charge, Element and Isotope Analysis System; ESUM = Extreme Solar Ultraviolet Monitor; EUVS = Extreme UV Spectrometer; SBUV = Solar Backscatter Ultraviolet; SEM = Solar EUV Monitor (EUV spectrometer); SOLSTICE = Solar Stellar Irradiance Comparison Experiment; SUSIM = Solar Ultraviolet Spectral Irradiance Monitor. SXP = Solar X-ray Photometer (Si photodiodes); SXT = Soft X-ray Telescope; XRS = X-ray sensor (ionization chamber);

Table 9.5 Observational indicators of solar activity[a]

Indicator	Description	Unit
Sunspot Number, *R* Since 1610	Number of dark regions of concentrated magnetic flux, best seen in white light spectroheliograms.	Number of sunspots or groups of sunspots
Plage Index, *PI* Since 1950	Sum of projected area *a* weighted by the observed intensity *I* of contiguous bright plage seen in Ca II *K* spectroheliograms at disc location $\mu = \cos\theta \cos\varphi$ for heliocentric latitude θ and longitude φ.	$10^3 \Sigma I a \mu$
10.7 cm Radio Flux, $F_{10.7}$ Since 1947	Full disc emission of 10.7 cm radiation from the upper chromosphere and corona, includes contributions from above both sunspots and plages.	(10^{22} W m^{-2} Hz^{-1})
Ca II *K* 1A Index, *K1A* Since 1976	Full-disc emission in a 1 (Å) core of the chromospheric Ca II *K* Fraunhofer line at 393.4 (nm) relative to emission in the nearby continuum.	
Helium I 1083-nm equivalent width since 1974	Full-disc measure of the equivalent width of the He 1083 (nm) line, primarily from the chromosphere, obtained by summing over digital spectroheliograms.	10^{-3}(Å)
Fe XIV 530.3-nm limb flux since 1973	Latitude-averaged intensity of coronal Fe XIV emission from an annulus of width 1.1 arc min centred at 1.15 solar radii above the limb.	10^{-6} × disc center brightness

[a]Source: Lean (1991); Owing to their common 11 year cycle, time series of all indicators are highly correlated with each other, but none of the time series is identical to another, because each may originate in different solar layers and reflect different emission mechanisms

Table 9.6 Solar UV irradiances and prominent solar emission lines (solar cycle 21)[a]

λ (Å)	Emitter	*I*(low) 1974	*I*(high) 1979	λ (Å)	Emitter	*I*(low) 1974	*I*(high) 1979
50–100		4.00 (8)	1.15 (9)	1031.91	O VI	2.10 (9)	9.04 (9)
100–150		1.50 (8)	3.43 (8)	1,000–1,050		2.47 (9)	8.67 (9)
150–200		2.37 (9)	4.85 (9)	1,050–1,100		2.80 (9)	5.45 (9)
200–250		1.56 (8)	3.70 (9)	1,100–1,150		9.10 (8)	1.65 (9)
256.30	He II, Si X	4.60 (8)	5.95 (8)	1,150–1,200		4.40 (9)	1.06 (10)
284.15	Fe XV	2.10 (8)	3.17 (9)	1215.67	H I	2.51 (11)	8.64 (11)
250–300		1.68 (8)	4.14 (9)	1,200–1,250		4.00 (9)	1.06 (10)
303.31	Si XI	8.00 (8)	2.50 (9)	1,250–1,300		4.10 (9)	8.56 (9)
303.78	He II	6.90 (9)	1.13 (10)	1302.17	O I	1.10 (9)	2.11 (9)
300–350		9.65 (8)	5.63 (9)	1304.86	O I	1.13 (9)	2.17 (9)
368.07	Mg IX	6.50 (8)	1.39 (9)	1306.03	O I	1.23 (9)	2.36 (9)
350–400		3.14 (8)	2.20 (9)	1334.53	C II	1.84 (9)	3.90 (9)
400–450		3.83 (8)	9.93 (8)	1335.71	C II	2.52 (9)	5.34 (9)
465.22	Ne VII	2.90 (8)	3.62 (8)	1,300–1,350		4.58 (9)	1.19 (10)
450–500		2.85 (8)	1.67 (9)	1393.76	Si IV	1.30 (9)	3.02 (9)
500–550		4.52 (8)	1.55 (9)	1,350–1,400		6.10 (9)	1.56 (10)
554.37	O IV[b]	7.20 (8)	1.59 (9)	1402.77	Si IV	9.10 (8)	2.11 (9)
584.33	He I	1.27 (9)	4.87 (9)	1,400–1,450		9.49 (9)	2.34 (10)
550–600		3.57 (8)	1.02 (9)	1,450–1,500		1.62 (10)	3.04 (10)
609.76	Mg X	5.30 (8)	1.46 (9)	1548.20	C IV	3.80 (9)	9.17 (9)
629.73	O V	1.59 (9)	3.02 (9)	1,500–1,550		2.52 (10)	4.47 (10)
600–650		3.42 (8)	4.82 (8)	1550.77	C IV	1.90 (9)	4.74 (9)
650–700		2.30 (8)	4.55 (8)	1561.0	C I[b]	2.50 (9)	3.37 (9)
703.31	O III[b]	3.60 (8)	7.17 (8)	1,550–1,600		3.56 (10)	4.66 (10)
700–750		1.41 (8)	4.26 (8)	1,600–1,650		5.60 (10)	9.52 (10)
765.15	N IV	1.70 (8)	4.32 (8)	1657.2	C I[b]	8.50 (9)	8.16 (9)
770.41	Ne VIII	2.60 (8)	6.71 (8)	1,650–1,700		1.22 (11)	1.87 (11)
789.36	O IV	7.02 (8)	1.59 (9)	1,700–1,750		2.25 (11)	2.96 (11)
750–800		7.58 (8)	2.18 (9)	1,750–1,800		3.57 (11)	4.33 (11)
800–850		1.63 (9)	5.01 (9)	1808.01	Si II	9.2 (9)	1.77 (10)
850–900		3.54 (9)	1.33 (10)	1816.93	Si II	1.52 (10)	2.73 (10)
900–950		3.00 (9)	1.20 (10)	1,800–1,850		5.81 (11)	6.77 (11)
977.02	C III	4.40 (9)	1.32 (10)	1,850–1,900		7.77 (11)	9.06 (11)
950–1,000		1.48 (9)	4.42 (9)	1,900–1,940		8.29 (11)	9.66 (11)
1025.72	H I	3.50 (9)	1.31 (10)				

[a]Powers of ten in parentheses; intensity units are (photon cm^{-2} s^{-1}). Intensities of emission lines are not included in the integrated intensities for the 50 (Å) intervals; they should be added to obtain the total intensity in the wavelength range. Roman numbers behind the emitting elements indicate the degree of ionization (I neutral, II singly ionized, III doubly ionized, etc.). Data assembled from Heroux and Hinteregger (1978), Hinteregger et al. (1981), Torr et al. (1979) and Torr and Torr (1985)

[b]Wavelengths for multiplets are approximate, integrated intensities are shown

Comments: The data were obtained with spectrometers onboard the Atmospheric Explorer E satellite. Rocket experiments during the period 1974–1981 were used to calibrate the spectra. The solar cycle 21 lasted from about 1974 to 1986 with a maximum of solar activity in 1980–1981. Data for minimum conditions were derived from observations in April 1974 when $F_{10.7} = 74 \times 10^{-22}$ (W m^{-2} Hz^{-1}), data for maximum conditions are from observations in February 1979 ($F_{10.7} = 243 \times 10^{-22}$ (W m^{-2} Hz^{-1})). The evaluation of these data went through several revisions until the final reference spectra were obtained (designated F74113 and F79050N, respectively). A detailed listing of irradiances as a function of wavelength (about 1,600 values) has been archived at the US National Space Science Data Center.

The failure to reproduce photoelectron fluxes observed with instruments onboard the Atmospheric Explorer E satellite by calculations based on the F74113 spectrum has led to the recognition that intensities at wavelengths below 250 (Å) are too low and should be raised by a factor of 2–3 (see Richards et al. (1994) for a review). More recent X-ray measurements on the Student Nitric Oxide Explorer Satellite by Bailey et al. (2000) have confirmed this conclusion for the region 2–30 nm.

Table 9.7 UV Solar irradiances: reference spectrum for solar cycle 22[a]

λ (Å)	*I*(min)	R_{27d}	R_{11a}	λ (Å)	*I*(min)	R_{27d}	R_{11a}	λ (Å)	*I*(min)	R_{27d}	R_{11a}
5	5.01 (3)	3.0	100	265	2.40 (8)	1.64	4.10	525	1.24 (8)	1.56	3.19
15	1.00 (6)	6.0	20.0	275	5.28 (8)	1.57	3.27	535	1.55 /8)	1.21	1.59
25	1.00 (7)	3.0	10.0	285	3.89 (8)	1.72	6.21	545	1.12 (8)	1.16	1.38
35	2.85 (7)	1.66	4.70	295	2.47 (8)	1.49	2.47	555	5.01 (8)	1.17	1.42
45	6.82 (7)	1.56	3.29	305	7.46 (9)	1.24	1.57	565	1.49 (8)	1.19	1.52
55	1.91 (8)	1.42	2.26	315	1.11 (9)	1.48	2.41	575	1.43 (8)	1.22	1.64
65	1.94 (8)	1.44	2.37	325	6.30 (8)	1.74	7.28	585	8.00 (8)	1.24	1.71
75	2.56 (8)	1.37	2.11	335	6.41 (8)	1.74	7.23	595	1.93 (8)	1.16	1.41
85	1.77 (8)	1.41	2.12	345	7.06 (8)	1.48	2.41	605	5.42 (8)	1.49	2.49
95	2.48 (8)	1.31	1.80	355	5.62 (8)	1.53	2.77	615	2.53 (8)	1.16	1.38
105	1.00 (8)	1.27	1.68	365	7.80 (8)	1.53	2.79	625	1.06 (9)	1.21	1.51
115	7.98 (7)	1.22	1.64	375	2.40 (8)	1.10	1.17	635	2.57 (8)	1.22	1.64
125	5.48 (7)	1.22	1.61	385	1.06 (8)	1.10	1.17	645	6.65 (7)	1.16	1.38
135	5.69 (7)	1.22	1.63	395	9.55 (7)	1.17	1.43	655	4.91 (7)	1.21	1.58
145	1.65 (8)	1.40	2.05	405	1.64 (8)	1.17	1.43	665	4.88 (7)	1.16	1.38
155	1.61 (8)	1.54	2.98	415	1.01 (8)	1.73	6.50	675	4.87 (7)	1.17	1.44
165	3.48 (8)	1.28	1.72	425	9.46 (7)	1.10	1.17	685	1.67 (8)	1.20	1.48
175	1.56 (9)	1.36	1.86	435	1.85 (8)	1.30	1.60	695	1.19 (8)	1.25	1.61
185	6.71 (8)	1.49	2.45	445	9.06 /(7)	1.10	1.17	705	3.48 (8)	1.16	1.39
195	6.05 (8)	1.57	3.11	455	8.38 (7)	1.22	1.64	715	1.49 (8)	1.18	1.47
205	2.64 (8)	1.61	3.77	465	2.96 (8)	1.33	1.75	725	1.03 (8)	1.24	1.72
215	1.93 (8)	1.65	4.28	475	1.26 (8)	1.22	1.64	735	1.36 (8)	1.24	1.72
225	4.42 (8)	1.46	2.46	485	2.17 (8)	1.21	1.59	745	1.68 (8)	1.24	1.72
235	2.47 (8)	1.42	2.26	495	4.25 (8)	1.59	3.65	755	2.77 (8)	1.21	1.58
245	6.00 (8)	1.48	2.49	505	3.40 (8)	1.19	1.51	765	7.33 (8)	1.19	1.50
255	9.68 (8)	1.51	2.71	515	1.15 (8)	1.21	1.59	775	5.43 (8)	1.40	2.10

(continued)

Table 9.7 (continued)

λ (Å)	*I*(min)	R_{27d}	R_{11a}	λ (Å)	*I*(min)	R_{27d}	R_{11a}	λ (Å)	*I*(min)	R_{27d}	R_{11a}
785	9.20 (8)	1.25	1.61	1195	2.80 (9)	1.17	1.39	1605	1.53 (10)	1.06	1.15
795	4.60 (8)	1.18	1.48	1205	7.50 (9)	1.27	1.73	1615	1.81 (10)	1.05	1.14
805	4.38 (8)	1.24	1.72	1215	3.76 (11)	1.22	1.64	1625	2.09 (10)	1.06	1.14
815	5.04 (8)	1.24	1.72	1225	3.16 (9)	1.17	1.33	1635	2.29 (10)	1.06	1.16
825	7.52 (8)	1.24	1.72	1235	2.22 (9)	1.24	1.37	1645	2.55 (10)	1.10	1.17
835	1.41 (9)	1.19	1.51	1245	1.70 (9)	1.21	1.37	1655	4.10 (10)	1.09	1.12
845	9.57 (8)	1.24	1.72	1255	1.66 (9)	1.16	1.32	1665	2.93 (10)	1.04	1.07
855	1.08 (9)	1.24	1.72	1265	2.30 (9)	1.21	1.50	1675	3.40 (10)	1.07	1.12
865	1.16 (9)	1.24	1.72	1275	1.33 (9)	1.17	1.29	1685	3.38 (10)	1.04	1.06
875	1.39 (9)	1.24	1.72	1285	1.11 (9)	1.16	1.25	1695	5.13 (10)	1.05	1.07
885	1.61 (9)	1.24	1.72	1295	1.25 (9)	1.18	1.38	1705	5.92 (10)	1.04	1.08
895	1.98 (9)	1.24	1.72	1305	1.05 (10)	1.15	1.29	1715	5.87 (10)	1.05	1.11
905	2.37 (9)	1.24	1.71	1315	1.80 (9)	1.12	1.19	1725	6.43 (10)	1.05	1.09
915	1.86 (9)	1.23	1.68	1325	1.36 (9)	1.14	1.25	1735	6.53 (10)	1.05	1.08
925	6.62 (8)	1.23	1.70	1335	1.14 (10)	1.22	1.57	1745	8.07 (10)	1.05	1.07
935	5.98 (8)	1.22	1.65	1345	1.22 (9)	1.12	1.25	1755	9.98 (10)	1.05	1.08
945	4.29 (8)	1.23	1.67	1355	2.84 (9)	1.12	1.23	1765	1.09 (11)	1.04	1.07
955	2.74 (8)	1.17	1.44	1365	1.83 (9)	1.14	1.26	1775	1.31 (11)	1.04	1.08
965	2.88 (8)	1.17	1.44	1375	1.98 (9)	1.12	1.24	1785	1.47 (11)	1.05	1.08
975	5.00 (9)	1.20	1.54	1385	2.00 (9)	1.11	1.21	1795	1.44 (11)	1.05	1.08
985	5.96 (8)	1.18	1.45	1395	5.01 (9)	1.22	1.60	1805	1.76 (11)	1.07	1.12
995	9.29 (8)	1.18	1.45	1405	4.49 (9)	1.17	1.43	1815	2.11 (11)	1.08	1.15
1005	3.82 (8)	1.17	1.44	1415	2.91 (9)	1.10	1.22	1825	2.05 (11)	1.05	1.09
1015	4.46 (8)	1.17	1.44	1425	3.20 (9)	1.10	1.20	1835	2.21 (11)	1.05	1.09
1025	3.70 (9)	1.24	1.71	1435	3.73 (9)	1.10	1.21	1845	1.92 (11)	1.04	1.08
1035	3.88 (9)	1.23	1.69	1445	3.66 (9)	1.09	1.20	1855	2.20 (11)	1.04	1.08
1045	6.34 (8)	1.17	1.44	1455	3.97 (9)	1.09	1.20	1865	2.53 (11)	1.05	1.09
1055	5.42 (8)	1.17	1.44	1465	4.95 (9)	1.11	1.20	1875	2.94 (11)	1.04	1.09
1065	5.22 (8)	1.17	1.43	1475	6.29 (9)	1.07	1.16	1885	3.13 (11)	1.04	1.09
1075	5.60 (8)	1.17	1.43	1485	6.44 (9)	1.09	1.17	1895	3.53 (11)	1.04	1.10
1085	9.44 (8)	1.17	1.44	1495	5.83 (9)	1.08	1.17	1905	3.69 (11)	1.04	1.08
1095	6.41 (8)	1.17	1.44	1505	6.56 (9)	1.08	1.16	1915	4.06 (11)	1.04	1.09
1105	6.90 (8)	1.17	1.44	1515	7.13 (9)	1.08	1.16	1925	4.35 (11)	1.04	1.09
1115	7.18 (8)	1.10	1.17	1525	8.83 (9)	1.10	1.21	1935	3.32 (11)	1.03	1.08
1125	6.87 (8)	1.19	1.50	1535	9.95 (9)	1.10	1.20	1945	5.55 (11)	1.04	1.08
1135	6.21 (8)	1.10	1.17	1545	1.69 (10)	1.16	1.31	1955	5.43 (11)	1.04	1.08
1145	4.25 (8)	1.10	1.17	1555	1.45 (10)	1.12	1.24	1965	6.18 (11)	1.04	1.08
1155	7.03 (8)	1.10	1.17	1565	1.52 (10)	1.08	1.16	1975	6.30 (11)	1.04	1.07
1165	8.02 (8)	1.10	1.17	1575	1.38 (10)	1.06	1.16	1985	6.38 (11)	1.03	1.06
1175	2.97 (9)	1.19	1.51	1585	1.34 (10)	1.07	1.15	1995	6.97 (11)	1.03	1.06
1185	9.18 (8)	1.10	1.17	1595	1.36 (10)	1.06	1.13				

[a]Powers of ten are shown in parentheses, intensity units are (photon cm^{-2} s^{-1}); Source of data: Woods and Rottman (2002). Intensities outside Earth for solar minimum conditions are listed in 10 (Å) intervals (x ± 5 (Å)); R_{27d} and R_{11a} are solar cycle 22 variability ratios for the 27 day solar rotational period and the 11 year solar cycle. Variability ratios are maximum/minimum values for the time period of observation (1992–1997). Solar cycle 22 lasted from about 1986 to 1997

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9.4 Absorption and Photoionization Coefficients

Table 9.8 Ionization potentials of some important atmospheric constituents and the corresponding upper wavelength limits for photoionization by ultraviolet radiation[a]

Species	IP (ev)	λ_{IP} (nm)	Species	IP (ev)	λ_{IP} (nm)	Species	IP (ev)	λ_{IP} (nm)
Atoms								
H	13.5984	91.175	Mg	7.6462	162.151	Fe	7.9024	156.894
He	24.5874	50.426	Al	5.9858	207.132	Br	11.8138	104.949
Li	5.3917	229.953	Si	8.1517	152.097	Kr	13.9996	88.563
Be	9.3227	132.992	P	10.4867	118.230	Rb	4.1771	296.817
C	11.2603	110.107	S	10.3600	119.676	Sr	5.6949	217.713
N	14.5341	85.306	Cl	12.9676	95.613	I	10.4513	118.631
O	13.6181	91.044	Ar	15.7596	78.672	Xe	12.1298	102.214
F	17.4228	71.162	K	4.3407	285.634	Cs	3.8939	318.406
Ne	21.5645	57.495	Ca	6.1132	202.815	Ba	5.2117	237.898
Na	5.1391	241.258	Ti	6.8281	181.579	Hg	10.4375	118.787
Molecules								
H_2	15.426	80.374	NO	9.264	133.834	CH_3	9.843	125.962
OH	13.017	95.248	NO_2	9.586	129.339	CH_4	12.61	98.322
HO_2	11.350	109.237	CO	14.014	88.472	HF	16.044	77.278
H_2O	12.621	98.236	CO_2	13.773	90.020	HCl	12.749	97.250
H_2O_2	10.58	117.187	HCN	13.60	91.165	SO_2	12.349	100.400
O_2	12.070	102.721	CH	10.64	116.527	SO	10.294	120.443
N_2	15.581	79.574	CH_2	10.396	119.261	SF_6	15.32	80.930

[a]Data selected from Sansonetti and Martin (2005); see also National Institute of Standard Technology, http://webbook.nist.gov

Table 9.9 Ionization thresholds for excited states of oxygen and nitrogen ions[a]

	Term	ν' (cm^{-1})	λ_{IP} (Å)	IP (eV)
Atomic oxygen[b]				
O^+ ($2s^22p^3$) (ground state)	$^4S^0_{3/2}$	109837.39	910.44	13.618
O^+ ($2s^22p^3$)	$^2D^0_{5/2}$	136647.94	731.81	16.942
	$^2D^0_{3/2}$	136667.96	731.70	16.945
O^+ ($2s^22p^3$)	$^2P^0_{3/2}$	150305.40	665.31	18.635
	$^2P^0_{1/2}$	150307.39	665.30	18.636
O^+ ($2s2p^4$)	$^4P_{5/2}$	229674.60	435.40	28.476
	$^4P_{3/2}$	229837.82	435.09	28.496
	$^4P_{1/2}$	229920.25	434.93	28.506
O^+ ($2s2p^4$)	$^2D_{5/2}$	275825.85	362.55	34.198
O^+ ($2s2p^4$)	$^2D_{3/2}$	275833.89	362.54	34.199
O^+ ($2s2p^4$)	$^2S_{1/2}$	305547.86	327.28	37.883
O^+ ($2s2p^4$)	$^2P_{1/2}$	324007.31	308.64	40.172
	$^2P_{3/2}$	324067.06	308.58	40.179
K shell ionization		4288450.	23.32	531.7
Molecular oxygen[c]				
O_2^+ (ground state)	$X\ ^2\Pi_g$	97359.2	1027.1	12.071
O_2^+	$a\ ^4\Pi_u$	129890.1	769.9	16.1
O_2^+	$A\ ^2\Pi_u$	137525.9	727.1	17.1
O_2^+ (dissociating)[c]	$b\ ^4\Sigma_g^-$	146557.0	682.3	18.2
O_2^+ (dissociating)	$B\ ^2\Sigma_g^-$	163702.4	610.9	20.3
O_2^+ (dissociating repulsive)	$^2\Pi_u$	193573.4	516.6	24.0
Molecular nitrogen[d]				
N_2^+ (ground state)	$X\ ^2\Sigma_g^+$	125667.64	795.8	15.581
N_2^+	$A\ ^2\Pi_u$	134683.2	742.5	16.7
N_2^+	$B\ ^2\Sigma_u^+$	151233.7	661.2	18.8
N_2^+ (dissociating)	$C\ ^2\Sigma_u^+$	190209.7	525.7	23.6
N_2^+ (dissociating)	$F\ ^2\Sigma_g^+$	233900.8	427.5	29.0

[a]Term symbol, wave number $\nu' = 1/\lambda$, threshold wavelength λ_{IP}, ionization potential, IP

[b]Source: Sansonetti and Martin (2005)

[c]The threshold for dissociation occurs at 661.87 (Å) (18.732 eV) which coincides with the energy of the $N = 9$ rotational level, $\upsilon = 4$, of the $b\ ^4\Sigma_g^-$ state. Sources: Huber and Herzberg (1979), Samson et al. (1982)

[d]Predissociation occurs with $\upsilon = 3$ and higher vibrational levels of the $C\ ^2\Sigma_u^+$ state, coinciding with the threshold for dissociation at 509.66 (Å) (24.327 eV). Sources: Huber and Herzberg (1979), Samson et al. (1987)

Table 9.10a Photoionization cross sections of atomic oxygen (multiple ionization)[a]

	$\sigma(O^+)$	$\sigma(O^{2+})$	$\sigma(O^{3+})$		$\sigma(O^+)$	$\sigma(O^{2+})$	$\sigma(O^{3+})$
λ (Å)	(10^{-20} cm^2 atom^{-1})			λ (Å)	(10^{-20} cm^2 atom^{-1})		
44.3	15.0	1.05	0.027	82.2	62.0	10.3	0.220
45.9	15.4	1.20	0.032	88.6	72.0	12.1	0.202
47.7	16.1	1.30	0.037	95.4	86.0	14.2	0.165
49.6	16.8	1.50	0.044	103.3	101.0	16.4	0.101
51.7	18.0	1.75	0.054	112.7	120.0	18.5	0.028
53.9	19.7	2.05	0.069	124.0	144.0	20.5	–
56.4	22.0	2.55	0.087	137.8	184.0	22.1	–
59.0	25.0	3.20	0.107	155.0	237.0	23.0	–
62.0	28.6	3.90	0.128	177.1	320.0	22.5	–
65.3	33.0	4.80	0.151	206.6	425.0	18.7	–
68.9	39.0	5.80	0.175	248.0	575.0	2.0	–
72.9	45.0	6.90	0.195	254.4	600.0	0.0	–
77.5	52.0	8.40	0.212	260.0	615.0	0.0	–

[a]The threshold for formation of O^{2+} occurs at 254.38 (Å) (48.739 eV), that for O^{3+} at 119.59 (Å) (103.675 eV). Source of data: Angel and Samson (1988)

Table 9.10b Photoionization cross sections of atomic oxygen (260 – 910 Å)[a]

	$10^{18}\ \sigma$		$10^{18}\ \sigma$		$10^{18}\ \sigma$		$10^{18}\ \sigma$
λ (Å)	(cm^2 atom^{-1})	λ (Å)	(cm^2 atom^{-1})	λ (Å)	(cm^2 atom^{-1})	λ (Å)	(cm^2 atom^{-1})
270.0	6.50	479.43	15.60	690.0	9.80	760.0	3.90
280.0	6.85	486.6	12.65	690.6	9.47	760.22	4.06
290.0	7.40	490.0	12.0	692.2	9.51	765.0	4.00
300.0	7.55	500.0	11.9	692.5	9.60	780.0	3.70
303.8	7.70	510.0	11.9	693.8	9.00	785.0	3.70
310.0	7.90	520.0	12.0	695.3	9.06	825.0	3.30
320.0	8.25	530.0	12.1	705.0	9.60	830.0	3.30
330.0	8.60	540.0	12.3	705.9	9.71	835.0	3.30
340.0	8.92	550.0	12.5	707.6	9.88	840.0	3.30
350.0	9.25	560.0	12.7	709.2	9.71	845.0	3.25
360.0	9.57	570.0	12.9	710.0	9.15	850.0	3.20
370.0	9.90	580.0	13.0	710.8	9.30	855.0	3.10
380.0	10.20	590.0	13.2	712.5	9.26	860.0	3.10
390.0	10.50	600.0	13.3	714.1	9.18	865.0	3.10
400.0	11.80	610.0	13.4	715.7	9.24	870.0	3.10
410.0	11.00	620.0	13.4	717.6	8.79	885.0	2.85
416.0	11.17	630.0	13.4	719.2	9.00	890.0	2.70
420.0	11.30	640.0	13.3	720.0	9.00	895.0	2.75
430.0	11.50	650.0	13.0	720.9	8.91	900.0	2.85
436.67	11.38	660.0	12.6	722.5	9.02	905.0	2.75
449.0	11.42	665.3	12.0	727.5	8.90	907.5	2.75
457.5	12.26	677.5	10.0	729.0	9.17	909.8	2.45
462.0	12.22	682.8	9.69	730.6	8.40	910.0	1.15
464.3	11.17	683.0	9.65	732.2	8.03	910.5	0.70
471.53	11.25	683.9	9.25	752.3	4.15	911.0	0.15

[a]The threshold for formation of O^+ lies at 910.44 (Å) (13.618 eV). Source of data: Angel and Samson (1988), Samson and Pareek (1985). Smoothed experimental data are presented except in the region above 677.5 (Å) and between 430 and 490 (Å) where significant structure occurs

Table 9.11 State specific photoionization cross sections (10^{-18} cm^2 atom^{-1}) of atomic oxygen[a]

λ (Å)	$^4S^0$	$^2D^0$	$^2P^0$	^4P	^2P	O^{2+}	Total
50–100	0.190	0.206	0.134	0.062	0.049	0.088	0.730
100–150	0.486	0.529	0.345	0.163	0.130	0.186	1.839
150–200	0.952	1.171	0.768	0.348	0.278	0.215	3.732
200–250	1.311	1.762	1.144	0.508	0.366	0.110	5.202
250–300	1.628	2.325	1.488	0.637	0.383	0.00	6.461
300–350	2.259	3.446	2.173	0.815	0.00	0.00	8.693
350–400	2.523	3.883	2.422	0.859	0.00	0.00	9.687
400–450	3.073	4.896	2.986	0.541	0.00	0.00	11.496
450–500	3.394	5.459	3.274	0.00	0.00	0.00	12.127
500–550	3.421	5.427	3.211	0.00	0.00	0.00	12.059
550–600	3.620	5.910	3.494	0.00	0.00	0.00	13.024
600–650	4.250	6.159	2.956	0.00	0.00	0.00	13.365
650–700	5.128	11.453	0.664	0.00	0.00	0.00	17.245
700–750	6.739	3.997	0.00	0.00	0.00	0.00	10.736
750–800	5.091	0.00	0.00	0.00	0.00	0.00	5.091
800–850	3.498	0.00	000	0.00	0.00	0.00	3.498
850–900	4.554	0.00	0.00	0.00	0.00	0.00	4.554
900–950	1.315	0.00	0.00	0.00	0.00	0.00	1.315

[a]Weighted by EUV solar minimum reference spectrum F74113 (April 1974). Source of data: Richards et al. (1994). For energy thresholds see Tables 9.9 and 9.10a

Table 9.12 Photoionization cross sections of atomic hydrogen[a]

λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})	λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})	λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})
10	5.55 (−6)	200	8.33 (−2)	600	2.02
20	5.56 (−5)	250	1.62 (−1)	650	2.53
30	2.10 (−4)	300	2.78 (−1)	700	3.10
40	5.39 (−4)	350	4.36 (−1)	750	3.74
50	1.10 (−3)	400	6.43 (−1)	800	4.46
75	4.02 (−3)	450	9.01 (−1)	850	5.26
100	9.92 (−3)	500	1.22	900	6.12
150	3.47 (−2)	550	1.59	911.753	6.31

[a]Powers of ten are shown in parentheses. Calculated from theory; Source: Samson (1966)

Comments: The theoretical formula for the photoionization of atomic hydrogen is expected to be precise. The cross section is given by

$$\sigma = g\ Ry\left(e^2 / \varepsilon_0 h\nu\right)^3 / \left(2\pi\ 3^{3/2}\ \mathrm{n}^5\right) = 1.045\ g\ \lambda^3\left[\mathrm{m}^2\right]$$

where *Ry* is the Rydberg constant, *e* is the elementary charge, ε_0 is the permittivity of vacuum, *h* is the Planck constant, *ν* is the frequency, n is the principal quantum number (here, n = 1), and *g* is the Gaunt factor, which is a function of frequency. The Gaunt factor varies from 0.8 at threshold to a maximum of unity at approximately 200 (Å), then falls rapidly to very low values in the X-ray region. Gaunt factors have been calculated and tabulated by Karzas and Latter (1961), and these data were used in the calculations.

Table 9.13 Photoionization cross sections of helium[a]

λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})	λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})	λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})	λ (Å)	$10^{18}\,\sigma$ (cm^2 atom^{-1})
30.0	0.008	160.0	0.85	290.0	2.79	420.0	5.50
40.0	0.016	170.0	0.93	300.0	2.96	430.0	5.72
50.0	0.029	180.0	1.00	310.0	3.17	440.0	5.95
60.0	0.050	190.0	1.24	320.0	3.35	450.0	6.17
70.0	0.083	200.0	1.45	330.0	3.56	460.0	6.40
80.0	0.12	210.0	1.45	340.0	3.79	470.0	6.63
90.0	0.19	220.0	1.63	350.0	3.97	480.0	6.85
100.0	0.27	230.0	1.74	360.0	4.20	490.0	7.08
110.0	0.37	240.0	1.90	370.0	4.35	500.0	7.32
120.0	0.47	250.0	2.06	380.0	4.61	502.0	7.36
130.0	0.56	260.0	2.22	390.0	4.84	503.0	7.38
140.0	0.66	270.0	2.41	400.0	5.06	504.0	7.42
150.0	0.76	280.0	2.59	410.0	5.30	505.0	0.00

[a]The photoionization cross section is a continuous function of wavelength; the ionization threshold occurs at 504.26 (Å) (24 587 eV), where the photoionization cross section rises sharply to its peak value. Source: Kirby et al. (1979). Theoretical and experimental data differ by less than 5%

Table 9.14a Photoionization cross sections of molecular nitrogen (30 – 520 Å)[a]

λ (Å)	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	$\sigma(N^+)$ (10^{-18} cm^2 molecule^{-1})	λ (Å)	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	$\sigma(N^+)$ (10^{-18} cm^2 molecule^{-1})	λ (Å)	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	$\sigma(N^+)$ (10^{-18} cm^2 molecule^{-1})
30.0	0.05	0.02	135.0	1.69	0.87	240.0	5.91	3.59
35.0	0.07	0.03	140.0	1.84	0.93	245.0	6.17	3.63
40.0	0.09	0.05	145.0	2.00	0.98	250.0	6.45	3.57
45.0	0.12	0.06	150.0	2.14	1.07	255.0	6.71	3.47
50.0	0.15	0.08	155.0	2.28	1.18	260.0	6.99	3.29
55.0	0.19	0.10	160.0	2.41	1.30	265.0	7.20	3.20
60.0	0.23	0.12	165.0	2.57	1.40	270.0	6.44	3.06
65.0	0.28	0.15	170.0	2.74	1.50	260.0	6.99	3.29
70.0	0.34	0.18	175.0	2.91	1.60	265.0	7.20	3.20
75.0	0.39	0.21	180.0	3.08	1.73	270.0	6.44	3.06
80.0	0.46	0.24	185.0	3.26	1.90	275.0	7.68	2.93
85.0	0.54	0.29	190.0	3.45	2.05	280.0	7.88	2.90
90.0	0.66	0.33	195.0	3.65	2.18	285.0	8.14	2.78
95.0	0.72	0.38	200.0	3.87	2.33	290.0	8.40	2.70
100.0	0.82	0.43	205.0	4.10	2.48	295.0	8.65	2.62
105.0	0.94	0.50	210.0	4.35	2.64	300.0	8.91	2.59
110.0	1.03	0.55	215.0	4.58	2.82	303.8	9.16	2.54
115.8	1.15	0.63	220.0	4.94	3.01	310.0	9.57	2.45
120.0	1.95	0.67	225.0	5.10	3.18	315.0	9.90	2.45
125.0	1.41	0.74	230.0	5.36	3.35	320.0	10.30	2.43
130.0	1.54	0.83	235.0	5.64	3.48	325.0	10.68	2.45

(continued)

Table 9.14a (continued)

λ (Å)	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	$\sigma(N^+)$ (10^{-18} cm^2 molecule^{-1})	λ (Å)	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	$\sigma(N^+)$ (10^{-18} cm^2 molecule^{-1})	λ (Å)	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	$\sigma(N^+)$ (10^{-18} cm^2 molecule^{-1})
330.0	11.11	2.44	390.0	17.90	1.15	470.0	22.15	1.12
335.0	11.60	2.35	400.0	19.00	1.07	480.0	22.35	1.25
340.0	12.20	2.18	410.0	20.00	1.02	490.0	22.60	0.90
345.0	12.70	2.12	420.0	21.00	0.85	495.0	22.85	0.65
350.0	13.30	1.98	430.0	21.72	0.92	500.0	23.15	0.35
360.0	14.40	1.78	440.0	22.15	0.95	505.0	23.50	0.08
370.0	15.58	1.50	450.0	22.20	0.90	510.0	23.80	0.03
380.0	16.80	1.23	460.0	22.05	1.00	520.0	24.58	0.00

[a] The cross sections are smooth functions of λ in the wavelength region covered; the total ionization cross section is $\sigma(\text{ion}) = \sigma(\text{abs}) = \sigma(N_2^+) + \sigma(N^+)$. The energy threshold for the formation of N^+ occurs at 509.66 (Å) (24.327 eV). Source of data: Samson et al. (1987) for the wavelength range >115 (Å). At lower wavelengths, the total ionization cross sections reported by Denne (1970) were interpolated; it was assumed that the nearly constant ratio $\sigma(N^+)/\sigma(\text{ion})$ observed between 115 and 140 (Å) extends into the region below 100 (Å)

Table 9.14b Absorption and photoionization cross sections of N_2 (530 – 800 Å)[a]

λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	$\sigma(N_2^+)$ (10^{-18} cm^2 molecule^{-1})
530.0	25.07	25.07	668.0	22.40	21.20	679.2	30.29	19.68
540.0	25.30	25.30	669.0	48.40	46.10	679.9	34.08	8.76
550.0	24.70	24.70	669.6	32.32	30.86	680.2	35.70	32.80
560.0	23.40	23.40	670.0	21.60	20.70	680.4	34.67	31.95
570.0	22.50	22.50	670.4	22.00	21.40	680.7	33.14	30.67
580.0	22.40	22.40	671.0	28.71	26.40	681.0	31.60	29.40
590.0	22.40	22.40	671.5	34.30	33.30	681.3	25.30	23.50
600.0	22.58	22.58	671.9	28.40	27.50	681.4	32.80	30.49
610.0	22.80	22.80	672.9	23.00	21.40	681.6	47.80	44.60
620.0	23.10	23.10	673.6	23.00	20.83	681.7	55.30	51.44
630.0	23.38	23.38	673.8	23.00	20.50	682.0	77.80	72.40
640.0	23.66	23.66	674.0	30.41	14.80	682.3	65.57	59.38
650.0	23.95	23.95	674.4	45.24	27.60	682.8	45.18	37.68
660.0	24.20	24.20	675.0	67.49	28.70	683.0	37.03	29.00
661.0	25.22	23.00	675.2	74.90	61.40	683.3	24.80	23.30
661.4	25.74	23.36	675.7	65.77	38.71	683.9	24.36	22.90
661.9	26.40	23.80	676.0	60.30	25.10	684.8	23.70	22.30
663.0	26.69	21.00	676.2	56.65	24.08	685.5	23.70	22.96
664.0	26.94	24.30	676.6	49.35	22.04	686.0	23.70	22.50
664.6	27.10	25.20	677.0	42.05	20.00	686.6	23.69	21.71
664.9	25.60	23.80	677.5	32.93	20.85	687.0	23.67	20.67
665.3	27.47	25.60	677.9	25.62	21.53	687.9	23.62	18.31
666.0	27.40	25.60	678.3	25.42	22.03	688.4	23.60	17.00
667.0	30.00	28.20	678.8	28.13	22.58	689.0	23.60	15.80
667.3	40.40	38.10	679.0	29.21	22.80	690.0	23.33	13.70

(continued)

Table 9.14b (continued)

λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (N_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (N_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (N_2^+) (10^{-18} cm^2 molecule^{-1})
690.6	23.16	9.08	715.0	18.55	4.50	736.5	31.80	14.80
691.0	23.05	6.00	715.6	14.50	3.60	737.0	26.40	9.20
691.2	23.00	12.20	716.0	16.26	3.00	737.2	24.04	11.96
691.4	23.00	17.90	716.5	18.46	6.75	737.5	20.50	16.10
692.0	23.80	18.10	717.0	20.66	10.50	738.0	18.20	23.70
692.4	25.13	20.03	717.2	21.54	10.60	738.4	21.84	18.18
692.7	27.91	24.31	718.0	25.06	11.00	739.0	27.30	9.90
693.0	30.69	28.60	718.5	23.20	17.55	739.2	26.56	9.92
693.8	38.10	35.72	719.0	27.40	24.10	740.0	23.60	10.00
694.0	39.96	37.50	719.4	26.71	20.06	740.2	22.34	9.50
694.3	42.74	40.59	720.0	25.66	14.00	741.0	17.30	7.50
694.9	48.30	44.77	720.9	24.10	12.83	741.2	17.48	8.02
695.2	76.10	62.98	721.4	27.48	24.00	742.0	18.20	10.10
696.0	61.30	43.70	721.8	30.19	18.53	742.4	16.20	8.38
696.5	52.05	32.90	722.0	31.54	15.80	743.0	13.20	5.80
697.0	42.80	22.10	722.5	34.92	25.70	743.2	17.92	8.72
697.3	37.25	22.25	722.9	37.62	33.62	743.5	25.00	13.10
697.5	33.55	22.35	723.4	69.30	34.60	743.7	27.72	11.42
697.7	29.85	22.45	723.9	59.51	33.35	744.0	31.80	8.90
698.0	24.30	22.60	724.2	53.63	31.00	744.5	46.50	17.60
698.9	22.89	22.33	724.8	41.88	24.70	744.9	34.72	12.56
699.4	22.10	20.80	724.9	39.92	23.65	746.0	15.90	6.30
700.0	23.80	22.40	725.5	30.60	19.15	746.4	18.62	6.14
700.4	22.59	21.27	726.0	29.24	15.70	746.7	20.66	6.02
701.0	25.50	24.10	726.4	28.16	16.10	747.0	22.70	5.90
701.6	28.26	26.80	727.0	26.53	16.70	747.5	51.12	21.90
702.0	30.10	28.60	727.3	25.71	13.82	748.0	38.60	11.30
703.0	28.30	27.10	727.5	25.17	11.90	748.5	28.60	8.85
703.36	26.54	25.48	728.0	24.17	7.10	749.0	18.60	6.40
704.0	23.40	22.60	728.3	23.63	6.86	750.0	33.20	10.00
704.5	25.80	25.00	729.0	22.94	6.30	750.7	25.85	5.87
705.0	25.79	22.30	729.4	23.00	10.54	751.0	22.70	4.10
705.9	25.78	21.13	729.8	23.05	14.78	751.6	20.00	4.76
707.0	25.77	19.60	730.0	23.08	16.90	752.0	18.20	5.20
707.9	25.76	19.06	730.9	23.20	12.58	752.3	16.82	4.99
708.9	25.75	18.19	731.5	22.68	9.04	752.9	14.06	4.57
710.0	25.74	17.80	732.0	22.24	13.10	754.0	27.30	13.80
711.0	25.73	18.00	732.5	21.81	10.95	754.4	61.94	46.12
711.9	25.72	18.00	733.0	21.37	8.80	755.0	30.00	28.50
712.5	25.71	17.30	733.3	21.11	9.22	755.2	44.00	24.74
712.9	25.71	16.74	734.0	20.50	10.20	755.5	25.00	19.10
713.5	25.70	15.40	734.5	30.50	15.10	755.8	22.00	16.22
713.9	25.70	14.44	735.0	25.00	11.30	756.0	20.00	14.30
714.7	20.57	7.41	735.9	20.95	9.05	756.2	17.00	12.22

(continued)

Table 9.14b (continued)

λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (N_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (N_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (N_2^+) (10^{-18} cm^2 molecule^{-1})
756.5	12.50	9.10	768.7	42.30	28.50	783.5	150.00	63.20
757.0	50.00	24.20	769.0	25.00	16.00	783.8	234.10	125.30
757.2	69.20	20.24	769.2	32.70	14.72	784.0	224.36	48.40
757.5	42.68	14.30	769.5	42.30	12.80	784.4	204.87	18.80
757.7	25.00	12.70	770.0	26.85	9.40	784.8	155.00	8.40
758.0	16.80	10.30	770.2	20.67	8.96	785.0	125.00	6.40
758.3	66.70	37.60	770.4	14.49	8.52	785.5	50.00	9.70
758.4	62.85	32.20	770.8	19.56	10.16	786.0	45.50	22.80
758.68	27.86	19.15	771.0	25.00	11.40	786.2	56.80	18.04
759.0	19.04	14.50	771.5	141.80	51.30	786.4	35.60	13.28
759.4	11.90	10.20	772.0	50.00	26.00	787.0	10.50	7.80
760.0	23.82	12.30	772.4	30.00	14.80	787.5	8.48	7.30
760.2	27.80	15.80	773.0	21.50	10.30	787.7	7.67	6.94
760.4	27.80	13.27	773.5	18.00	8.30	788.0	9.04	6.40
760.7	36.90	17.00	774.0	14.50	8.00	788.5	11.32	5.80
761.0	46.00	24.50	774.5	33.10	13.20	789.0	13.60	7.20
761.5	48.00	18.80	775.0	40.90	12.50	789.5	45.50	11.30
762.0	36.40	11.70	775.7	143.81	126.90	790.0	25.58	11.00
762.2	25.00	10.46	776.0	125.00	63.30	790.5	18.60	9.60
762.5	17.30	8.60	776.5	59.10	20.30	790.8	125.00	101.90
763.0	16.00	10.60	777.0	24.50	14.05	791.0	58.0	41.00
763.5	25.00	21.40	777.5	20.20	7.80	791.3	53.24	37.94
763.7	68.10	38.30	778.0	15.90	7.20	791.4	51.62	36.92
764.0	18.20	12.20	778.5	38.61	9.50	791.8	125.00	44.90
764.4	13.30	9.20	778.7	47.70	9.14	792.4	71.80	38.90
764.7	18.00	11.40	779.0	40.54	8.60	792.8	43.60	21.62
765.0	150.00	106.90	779.5	28.60	8.10	792.92	35.14	15.91
765.3	91.00	52.90	779.8	14.90	7.70	793.14	25.69	10.56
765.4	70.59	44.30	779.9	14.70	7.35	793.5	15.90	6.60
765.7	31.80	27.02	780.3	25.15	8.50	794.0	25.00	6.20
766.0	14.50	14.00	780.5	32.25	9.50	794.5	39.75	6.30
766.5	13.95	11.40	781.0	50.00	41.70	795.0	54.50	12.30
767.0	13.41	9.70	781.2	118.20	70.70	795.2	46.22	5.92
767.3	13.30	10.06	781.5	75.00	32.30	796.0	13.10	4.50
767.7	13.30	10.86	782.0	34.00	13.40	797.0	8.00	1.00
767.9	40.90	11.42	782.5	15.00	6.70	797.7	8.00	0.30
768.3	22.30	14.58	782.9	17.56	7.58	798.0	8.00	0.00
768.4	27.30	15.54	783.2	70.92	29.96	800.5	16.70	0.00

[a]The ionization threshold for the formation of N_2^+ occurs at 795.74 (Å) (15.581 eV); Source of data: Fennelly and Torr (1992), slightly condensed

Table 9.14c Absorption cross sections of molecular nitrogen (801 – 987 Å)[a]

λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})	λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})	λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})
801.0	40.00	815.5	6.70	838.0	13.30
801.5	104.00	816.0	14.00	838.6	41.32
802.0	40.00	816.42	24.92	838.9	55.33
802.6	16.60	816.77	33.92	840.0	3.00
803.0	1.00	817.0	40.00	840.5	1.00
803.5	3.85	817.19	44.94	840.7	50.00
804.0	6.70	817.5	53.00	841.0	26.70
804.27	7.82	817.78	60.20	841.5	20.00
804.38	8.30	818.0	66.00	842.0	96.70
804.5	8.80	818.2	71.20	842.5	13.30
804.78	9.96	818.34	74.84	843.0	6.70
805.0	10.90	818.5	79.00	843.5	3.00
805.29	12.14	819.0	92.00	843.8	1.80
805.44	12.75	819.5	12.00	844.0	1.00
805.74	56.86	819.8	6.60	844.5	26.70
806.0	18.00	820.0	3.00	845.0	13.30
806.23	95.95	820.5	7.30	845.5	3.00
806.42	159.70	821.0	26.70	845.9	1.40
807.0	46.70	821.3	18.66	847.0	1.00
808.0	6.70	821.5	13.30	848.0	1.00
808.2	4.42	822.0	3.00	849.0	1.00
808.5	1.00	823.0	3.00	849.2	7.28
808.8	33.30	824.0	3.00	849.5	16.70
809.0	33.30	824.5	8.00	850.0	46.70
809.3	13.92	824.9	12.24	850.6	26.66
809.5	1.00	825.3	8.92	851.0	13.30
810.0	8.00	825.5	6.00	851.5	6.70
810.5	4.50	826.0	33.00	851.8	4.48
810.66	3.35	826.5	25.30	852.0	3.00
810.85	2.05	826.8	18.10	853.0	3.00
811.0	1.00	827.0	13.30	853.2	36.48
811.26	1.96	827.5	3.00	853.5	86.70
811.49	2.81	|	|	854.0	66.70
811.61	3.26	832.9	3.00	854.5	46.70
811.8	3.96	833.5	5.30	855.0	20.00
812.0	4.70	833.7	8.50	855.5	13.30
812.27	15.50	834.0	13.30	856.0	3.00
812.5	24.70	834.5	13.30	856.2	173.30
812.8	100.00	835.0	83.30	856.5	20.00
813.0	33.40	835.2	180.00	857.0	8.70
813.5	50.00	835.4	135.75	857.3	12.13
813.7	62.00	836.0	3.00	857.7	16.70
814.0	80.00	837.0	3.00	858.0	13.30
814.5	14.70	837.5	20.00	858.5	6.70
814.9	11.50	837.8	15.98	859.0	3.00

(continued)

Table 9.14c (continued)

λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})	λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})	λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})
860.0	3.00	881.5	67.00	901.5	27.00
860.4	1.00	882.0	51.00	902.0	6.00
861.0	6.00	882.5	1.00	903.0	10.00
861.5	1.00	882.7	54.00	903.5	1.00
862.0	1.00	883.0	27.00	903.8	5.20
863.0	1.00	883.3	16.80	904.0	8.00
863.2	33.40	883.5	10.00	904.5	14.00
864.0	6.00	884.0	1.00	905.0	12.00
864.6	3.00	884.5	3.00	905.5	10.00
865.0	1.00	885.0	1.00	906.0	3.00
865.2	86.70	885.5	3.00	906.4	1.40
865.4	106.70	885.8	6.60	907.0	1.00
866.0	3.00	886.0	9.00	907.4	1.00
866.5	1.00	886.5	15.00	908.0	15.00
867.0	65.00	886.9	80.00	908.5	15.00
867.5	32.00	887.5	18.00	909.0	9.00
868.0	14.00	888.0	30.00	909.5	6.00
868.5	11.00	888.5	12.00	909.8	4.20
869.0	10.00	889.0	20.00	910.0	3.00
869.5	6.00	889.5	14.00	910.4	1.00
870.0	3.00	890.0	12.00	911.0	14.00
870.8	120.00	890.5	3.00	911.5	6.00
871.0	25.00	891.0	67.00	911.7	3.40
871.4	26.00	891.5	25.00	912.0	1.00
872.0	80.00	892.0	15.00	912.5	1.00
872.5	33.00	892.5	15.00	913.0	82.00
873.0	12.00	893.0	1.00	913.3	53.80
873.5	10.00	893.5	14.00	913.5	35.00
874.0	6.00	894.0	10.00	914.0	15.00
874.5	3.00	894.5	3.00	914.5	3.00
875.0	3.00	895.0	3.00	915.0	3.00
875.5	3.00	896.0	3.00	915.5	1.00
876.0	107.00	896.5	25.00	916.0	1.00
876.2	60.00	897.0	11.00	916.5	42.00
876.5	54.00	897.2	104.00	917.0	1.00
877.0	30.00	897.5	64.00	917.2	1.80
877.5	24.00	898.0	1.00	917.5	3.00
877.72	23.12	898.5	3.00	918.0	6.00
878.5	20.00	898.7	4.20	918.5	3.00
878.92	13.28	899.0	6.00	918.9	3.00
879.2	9.60	899.5	10.00	919.5	1.00
879.5	6.00	900.0	12.00	919.9	97.00
879.8	4.20	900.2	11.20	920.4	50.75
880.0	3.00	900.5	10.00	920.96	27.64
880.5	5.00	901.0	3.00	921.5	17.00
881.0	110.00	901.3	31.00	922.0	11.00

(continued)

Table 9.14c (continued)

λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})	λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})	λ (Å)	$10^{18}\ \sigma$ (cm^2 molecule^{-1})
922.5	3.00	942.0	22.00	967.0	31.00
922.8	58.00	942.4	1.00	967.5	20.00
923.0	17.00	943.0	27.00	968.0	27.00
923.5	18.50	943.3	22.80	969.0	10.00
923.7	19.10	943.5	20.00	969.5	3.00
924.0	20.00	944.0	11.00	970.0	6.00
924.3	15.20	944.5	11.00	970.4	2.00
924.5	12.00	945.0	1.00	971.0	1.00
925.0	22.00	946.0	1.00	971.5	6.00
925.5	3.00	947.0	3.00	972.0	27.00
926.0	14.00	948.0	3.00	972.5	120.00
926.2	9.60	948.5	1.00	972.9	94.40
926.4	5.20	949.0	1.00	973.5	31.00
927.0	18.00	949.5	25.00	974.0	20.00
927.6	13.20	949.74	13.48	974.5	3.00
928.0	10.00	950.0	1.00	975.0	5.00
928.5	2.00	950.3	17.20	975.3	3.80
929.0	2.00	950.5	28.00	975.5	3.00
930.0	29.00	951.0	2.00	976.0	3.00
930.5	3.00	952.0	2.00	976.5	1.00
930.75	4.50	953.0	12.00	977.0	2.00
931.0	6.00	954.0	3.00	977.5	8.00
931.5	6.00	955.0	6.00	978.0	5.00
931.9	15.00	955.9	18.60	978.5	2.00
932.4	8.20	956.5	12.00	979.0	88.00
933.0	7.00	956.7	8.40	979.5	33.00
933.38	4.72	957.0	3.00	980.0	27.00
933.5	4.72	957.5	6.00	980.5	22.00
934.0	10.00	958.0	18.00	981.0	26.00
934.5	11.30	958.2	134.00	981.5	11.00
935.0	5.00	958.5	53.00	982.0	14.00
935.3	12.00	958.8	62.00	982.5	25.00
935.5	7.00	959.0	47.00	983.0	23.00
936.0	6.00	959.5	21.00	983.3	18.20
936.5	6.00	960.0	1.00	983.5	15.00
937.0	1.00	960.5	98.00	984.0	17.00
937.5	7.00	961.0	51.00	984.5	15.00
937.8	20.50	961.5	30.00	985.0	15.00
937.9	25.00	961.9	20.40	985.2	13.00
938.5	1.00	962.5	10.00	985.5	10.00
939.0	148.00	962.8	5.80	985.9	22.00
939.3	106.00	963.0	3.00	986.3	0.00
939.5	78.00	964.0	3.00	987.0	0.00
940.0	27.00	965.0	3.00	988.0	0.00
940.5	29.00	965.5	1.00	989.0	0.00
941.0	18.00	966.0	67.00		
941.5	15.00	966.5	60.00		

[a]The data were derived from absorption cross sections reported by Carter (1972) for a spectral resolution of 0.04 (Å); Vertical bars indicate no change in the cross section values. Source of data: Fennelly and Torr (1992)

Comments: In the wavelength region above 660 (Å) the spectrum of nitrogen features multiple absorption band systems superimposed on an ionization continuum, which sets in at 796 (Å). At longer wavelength the absorption of solar radiation by nitrogen in the upper atmosphere must still be taken into account because it partially shields the ionization of oxygen. For this reason, the table is extended to include the strongly varying absorption features up to 987 (Å). At wavelengths below 660 (Å), absorption and ionization cross sections are identical.

Table 9.15a Photoionization cross sections of molecular oxygen (30 – 600 Å)[a]

	$\sigma(O_2^+)$	$\sigma(O^+)$		$\sigma(O_2^+)$	$\sigma(O^+)$		$\sigma(O_2^+)$	$\sigma(O^+)$
λ (Å)	(10^{-18} cm^2 molecule^{-1})		λ (Å)	(10^{-18} cm^2 molecule^{-1})		λ (Å)	(10^{-18} cm^2 molecule^{-1})	
30.0	0.01	0.12	250.0	8.10	4.70	470.0	17.1	4.95
40.0	0.02	0.24	260.0	8.67	5.03	480.0	17.3	5.26
50.0	0.04	0.39	270.0	9.12	5.59	490.0	17.7	5.29
60.0	0.08	0.58	280.0	9.65	5.85	500.0	18.1	5.51
70.0	0.14	0.82	290.0	10.2	5.94	510.0	18.5	5.53
80.0	0.24	1.06	300.0	10.7	6.03	520.0	19.1	5.43
90.0	0.38	1.38	310.0	11.2	5.77	530.0	20.0	4.93
100.0	0.57	1.64	320.0	11.7	5.52	540.0	20.7	4.67
110.0	0.82	1.90	330.0	12.1	5.20	544.7	21.1	4.15
120.0	1.13	2.11	340.0	12.6	4.95	548.9	21.3	4.55
130.0	1.58	2.37	350.0	12.9	4.91	550.0	21.5	4.42
140.0	2.11	2.51	360.0	13.3	4.70	551.4	21.7	4.24
150.0	2.56	2.76	370.0	13.9	4.54	555.6	21.6	4.53
160.0	3.02	3.02	380.0	14.1	4.74	560.0	21.6	4.51
170.0	3.51	3.20	390.0	14.4	4.80	570.0	21.4	4.44
180.0	4.07	3.26	400.0	14.8	4.79	580.0	20.6	4.24
190.0	4.60	3.55	410.0	15.2	4.81	585.8	18.1	3.72
200.0	5.09	3.77	420.0	15.5	4.77	588.9	16.1	3.18
210.0	5.65	3.92	430.0	15.8	4.87	590.0	16.1	3.28
220.0	6.14	4.16	440.0	16.2	4.79	594.7	24.6	3.14
230.0	6.78	4.32	450.0	16.6	4.82	596.7	24.6	3.14
240.0	7.35	4.55	460.0	16.8	4.93	600.0	25.7	2.93

[a] The cross sections are smooth functions of λ in the wavelength region covered; the total ionization cross section is $\sigma(\text{ion}) = \sigma(\text{abs}) = \sigma(O_2^+) + \sigma(O^+)$. Source of data: Samson et al. (1982) for the wavelength range >120 nm. At lower wavelengths, the total ionization cross sections reported by Denne (1970) were interpolated, and the trend in the decrease of $\sigma(O_2^+)/\sigma(\text{ion})$ below 150 nm was extrapolated by using a quadratic function fitted to the data of Samson et al. (1982)

Table 9.15b Absorption and photoionization cross sections of O_2 (600 – 665 Å)[a]

	σ (abs)	σ (O_2^+)	σ (O^+)		σ (abs)	σ (O_2^+)	σ (O^+)
λ (Å)	(10^{-18} cm^2 molecule^{-1})			λ (Å)	(10^{-18} cm^2 molecule^{-1})		
604.3	30.1	26.9	2.50	636.3	27.9	26.1	1.01
608.9	26.4	23.7	1.91	637.3	25.3	23.5	1.01
610.8	30.1	27.1	1.82	638.1	27.9	26.1	1.01
612.7	23.1	20.7	1.60	638.7	25.3	23.5	1.01
613.1	28.3	25.6	1.50	642.5	29.0	27.1	1.05
615.2	28.6	26.5	1.40	644.2	20.8	19.4	1.10
616.3	24.2	22.1	1.30	645.0	25.3	23.4	1.10
617.7	34.6	32.2	1.20	645.9	24.9	23.0	1.12
618.2	28.3	26.1	1.15	646.7	30.1	28.3	1.12
618.7	29.8	27.5	1.12	649.4	25.3	23.4	1.15
620.5	23.1	21.4	1.05	651.8	29.7	27.5	1.16
621.9	32.7	30.6	1.00	654.0	28.8	26.8	1.04
624.5	25.3	23.6	0.95	656.0	28.0	26.3	0.98
626.6	29.0	30.2	0.95	658.0	27.1	25.7	0.89
627.1	24.9	29.2	0.96	660.0	26.3	25.1	0.75
629.6	32.4	30.2	0.97	661.0	25.9	24.8	0.25
633.0	23.4	21.7	0.98	661.4	25.7	24.6	0.10
634.4	31.2	29.4	0.99	661.9	25.5	24.5	0.00
635.8	25.3	23.5	1.00	665.8	23.8	23.0	0.00

[a]The total ionization cross section is $\sigma(\text{ion}) = \sigma(O_2^+) + \sigma(O^+)$. The threshold for the formation of O^+ is 661.87 (Å) (18.732 eV). Source of data: Matsunaga and Watanabe (1967), Samson et al. (1982)

Table 9.15c Absorption and photoionization cross sections of O_2 (670 – 1077 Å)[a]

	σ (abs)	σ (O_2^+)		σ (abs)	σ (O_2^+)		σ (abs)	σ (O_2^+)
λ (Å)	(10^{-18} cm^2 molecule^{-1})		λ (Å)	(10^{-18} cm^2 molecule^{-1})		λ (Å)	(10^{-18} cm^2 molecule^{-1})	
669.6	22.7	21.9	684.9	27.1	26.4	703.1	29.0	25.3
670.0	20.8	20.1	686.1	16.7	16.4	703.6	26.0	22.7
670.5	21.6	20.8	686.6	23.8	23.0	705.3	63.2	55.0
673.6	19.3	18.6	687.9	16.7	16.4	706.6	24.9	21.2
675.0	21.6	20.8	688.7	20.8	20.8	707.9	26.4	22.7
675.7	20.1	19.3	689.1	16.4	15.6	708.9	25.7	21.9
676.2	21.6	20.8	690.1	26.0	25.7	709.3	26.8	22.7
676.6	20.1	19.3	691.3	17.8	16.0	709.7	25.7	21.2
677.0	21.2	20.4	692.4	34.6	29.7	711.0	41.6	35.7
679.2	18.2	17.5	694.0	18.2	17.1	711.9	32.3	25.7
679.9	23.8	23.0	695.2	30.5	27.9	712.9	37.9	31.2
680.7	19.3	18.6	696.0	19.3	17.5	714.0	33.1	27.1
681.1	22.3	21.6	697.3	30.5	27.5	714.7	34.9	28.6
681.4	21.9	21.2	697.7	31.6	28.6	716.0	29.0	23.8
681.6	22.3	21.6	698.3	34.6	31.2	716.5	30.5	25.3
682.3	18.6	18.6	699.6	23.4	21.6	717.2	27.5	20.0
682.8	21.9	21.2	700.8	34.9	30.1	717.6	29.7	24.5
683.8	17.5	16.4	701.6	19.0	16.4	719.4	24.9	20.1

(continued)

Table 9.15c (continued)

λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (O_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (O_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (O_2^+) (10^{-18} cm^2 molecule^{-1})
720.4	34.2	24.9	764.6	17.5	9.67	809.3	22.3	9.29
721.3	26.8	21.9	765.4	22.3	11.9	811.8	55.0	15.2
721.8	27.5	23.8	766.7	19.0	10.0	812.5	29.4	8.18
722.6	25.7	20.4	768.4	17.1	11.5	813.7	34.9	9.67
722.9	26.0	20.8	768.8	20.8	13.0	814.9	18.6	9.29
723.4	25.3	20.1	769.2	17.8	11.2	817.2	45.4	21.9
724.2	27.5	22.7	769.6	21.2	13.0	818.2	20.1	7.06
725.0	25.3	21.6	770.2	15.2	9.29	819.8	31.6	11.2
726.4	49.1	36.4	770.5	20.4	11.5	821.3	16.0	6.55
727.3	30.1	25.3	770.8	19.7	9.67	823.2	28.3	11.2
728.3	30.5	25.7	771.6	24.2	10.4	824.1	16.0	6.32
729.0	27.9	23.4	772.4	23.8	10.0	924.9	24.2	8.92
729.4	29.8	25.03	773.1	26.8	14.1	825.3	20.1	7.06
729.8	29.0	24.5	775.1	13.8	10.8	826.0	29.0	10.4
731.1	35.3	29.7	778.1	29.4	17.8	826.8	11.9	5.58
731.8	31.6	27.1	778.8	24.5	13.0	827.8	12.3	5.95
732.5	51.3	44.2	780.0	27.9	10.8	828.3	11.2	5.95
733.3	32.7	29.7	781.5	14.5	11.2	829.4	22.7	8.18
735.3	35.3	31.6	782.9	20.8	9.29	829.6	22.3	7.81
737.2	32.3	29.7	783.2	20.4	8.92	829.8	23.0	8.55
737.5	34.2	31.2	784.4	25.7	11.2	831.0	10.8	4.09
739.3	24.9	22.7	784.8	23.8	10.0	832.5	32.7	9.67
740.0	25.7	21.9	786.0	26.8	10.8	834.1	10.4	4.09
741.2	20.1	17.5	786.4	19.7	10.0	834.5	10.8	4.46
742.2	21.6	18.6	787.6	25.7	15.2	835.4	10.0	4.09
743.2	17.8	13.4	788.0	24.2	16.4	836.3	17.1	5.58
745.0	20.4	16.7	788.6	27.5	11.2	837.8	11.2	4.09
746.4	18.6	14.9	789.0	26.8	10.8	838.6	24.5	10.8
747.0	21.2	16.7	790.0	28.3	11.5	838.9	23.4	10.4
748.0	15.6	11.5	791.3	21.2	9.29	839.1	24.9	10.8
750.0	23.8	14.9	792.4	27.9	11.8	842.1	8.18	3.05
751.0	17.5	11.5	792.8	24.2	11.8	843.8	12.3	4.09
751.6	19.0	13.8	794.1	33.8	12.3	844.6	10.0	3.72
752.9	14.9	10.0	795.0	23.0	7.43	845.9	18.6	5.20
755.0	23.4	14.5	795.2	23.4	8.18	847.6	7.43	2.45
756.0	19.0	11.2	796.0	21.9	7.43	848.5	7.81	2.97
756.2	19.3	13.4	797.7	31.6	16.0	849.2	7.43	3.23
758.0	17.5	10.8	798.1	26.8	12.3	850.6	9.67	4.46
758.4	19.3	12.3	799.5	39.8	14.5	851.8	8.55	3.42
759.4	17.1	10.4	801.6	27.1	7.43	853.2	12.6	5.58
760.7	21.2	11.2	802.6	34.2	11.2	955.0	7.06	3.01
761.5	19.3	10.4	803.5	26.0	13.0	857.3	10.0	4.09
762.1	19.7	11.2	805.1	49.1	12.3	859.2	6.69	2.86
762.5	19.3	10.8	807.0	27.9	10.0	861.0	7.43	3.05
763.2	21.9	13.0	808.2	36.4	13.4	864.6	9.29	4.46

(continued)

Table 9.15c (continued)

λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (O_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (O_2^+) (10^{-18} cm^2 molecule^{-1})	λ (Å)	σ (abs) (10^{-18} cm^2 molecule^{-1})	σ (O_2^+) (10^{-18} cm^2 molecule^{-1})
867.6	5.58	2.90	960.0	2.49	1.71	1022.4	1.30	1.12
870.0	8.18	5.20	961.9	15.6	12.6	1023.4	1.86	1.12
870.6	7.81	4.83	962.8	6.69	5.20	1024.6	1.00	1.00
871.4	10.0	5.95	965.5	50.9	37.9	1025.3	1.78	0.97
875.2	5.58	3.31	970.4	2.41	2.04	1025.7	1.64	0.95
878.1	1.34	8.55	972.5	31.6	22.7	1027.6	1.16	0.20
883.3	4.83	3.31	972.9	42.8	29.7	1028.2	0.67	0.00
885.8	1.78	1.15	974.5	5.57	3.42	1029.3	1.90	0.00
889.1	1.34	3.05	975.3	26.8	9.67	1030.2	0.82	
891.6	10.8	7.06	980.5	2.42	1.67	1031.0	1.49	
893.1	5.58	4.46	983.3	46.1	31.2	1032.3	1.00	
894.0	11.2	7.43	985.2	4.83	3.72	1033.1	1.08	
895.8	5.58	3.35	985.9	7.43	5.20	1033.6	0.89	
897.3	7.43	5.20	988.0	2.97	2.42	1034.9	1.67	
898.7	4.83	4.09	988.5	4.83	4.46	1036.5	0.52	
900.2	8.92	5.20	989.6	1.49	1.30	1036.9	0.97	
901.1	13.4	8.18	992.9	16.9	20.1	1037.2	0.67	
902.0	9.67	5.95	993.2	21.6	18.2	1038.0	1.90	
903.8	10.8	6.32	993.5	24.5	20.8	1038.8	0.71	
906.4	4.09	3.27	997.2	1.45	1.26	1039.4	1.78	
909.6	17.1	11.2	1000.0	1.49	1.26	1041.1	0.89	
910.0	15.2	10.0	1004.0	6.32	5.20	1041.9	1.23	
910.5	17.5	11.2	1004.3	5.58	4.46	1043.8	0.12	
913.5	4.83	3.35	1004.6	6.32	5.20	1047.1	2.57	
914.7	7.43	5.58	1006.8	1.38	1.19	1047.8	1.41	
915.6	4.09	2.71	1007.9	1.82	1.51	1049.5	2.49	
917.3	23.4	14.5	1009.1	1.41	1.20	1050.1	0.41	
920.4	3.01	2.12	1009.4	1.52	1.07	1051.1	1.12	
923.1	9.67	8.92	1010.0	1.45	0.90	1051.9	0.82	
923.5	8.92	7.81	1011.4	1.30	0.86	1052.4	2.16	
924.5	23.4	19.0	1012.3	1.08	0.80	1054.2	0.59	
926.4	3.72	3.16	1013.5	1.34	0.72	1054.8	1.97	
927.6	4.09	3.12	1013.9	1.12	0.75	1055.6	0.32	
928.1	3.35	2.71	1015.8	1.75	0.93	1058.3	1.04	
929.1	4.09	3.42	1016.0	1.19	0.90	1058.7	0.63	
930.0	3.72	3.20	1016.4	1.38	0.85	1059.6	1.15	
930.6	26.0	16.7	1016.9	1.08	0.79	1060.6	0.86	
931.5	12.3	8.18	1017.2	1.60	0.78	1060.9	1.15	
932.4	28.6	20.1	1017.8	0.97	0.76	1061.1	0.59	
935.6	2.83	2.19	1018.3	1.52	0.87	1061.7	1.15	
939.3	45.0	23.4	1018.8	1.08	0.97	1062.6	0.41	
944.6	2.64	2.30	1019.4	1.41	1.05	1064.2	3.05	
947.7	55.8	39.4	1020.0	1.28	1.08	1064.8	1.75	
950.3	2.23	1.97	1020.4	1.19	1.10	1066.4	3.42	
955.9	54.6	43.5	1020.8	1.60	1.13	1068.9	0.12	
956.7	29.0	22.3	1021.1	1.30	1.13	1073.9	2.01	
957.0	35.3	27.1	1021.6	1.64	1.20	1077.0	0.14	

[a] The threshold for the formation of O_2^+ lies at 1027.2 (Å) (12.07 eV). Source of data: Matsunaga and Watanabe (1967), Watanabe and Marmo (1956)

Comments: In the wavelength region above 540 (Å), the spectrum of oxygen exhibits considerable discrete structure in both ionization and absorption cross sections. Between 870 and 1,030 (Å) the absorption peaks are well separated and are superimposed on a weak continuum. The table of Matsunaga and Watanabe lists values for peaks and valleys.

Table 9.16 Absorption cross sections (cm^2 $molecule^{-1}$) of O_2 (1215.7 and 1250 – 1750 Å)[a]

λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{18}\,\sigma$
1215.7	0.0104	1299.0	0.520	1378.0	12.70	1550.0	7.84
1252.0	1.04	1302.0	0.444	1384.0	13.20	1560.0	7.34
1254.5	0.855	1306.0	0.357	1391.5	13.40	1570.0	6.49
1256.0	0.706	1309.0	0.516	1394.0	13.80	1580.0	5.94
1257.0	0.594	1312.5	0.721	1400.0	14.28	1590.0	5.22
1259.5	0.465	1317.0	1.10	1405.0	14.40	1600.0	4.75
1260.5	0.401	1321.5	1.60	1410.0	14.65	1610.0	4.04
1262.0	0.442	1325.0	2.05	1420.0	14.78	1620.0	3.45
1263.5	0.342	1329.0	2.31	1430.0	14.83	1630.0	2.92
1264.5	0.242	1333.5	2.29	1440.0	14.66	1640.0	2.48
1266.0	0.182	1336.5	2.20	1450.0	14.45	1650.0	2.16
1269.0	0.119	1339.5	2.24	1455.0	13.90	1660.0	1.78
1271.0	0.067	1343.0	2.79	1460.0	13.60	1670.0	1.48
1274.0	0.093	1345.0	3.64	1470.0	13.20	1680.0	1.24
1277.0	0.153	1349.0	5.76	1480.0	12.70	1690.0	0.973
1279.5	0.249	1351.0	7.10	1490.0	12.00	1700.0	0.843
1283.5	0.364	1355.0	7.10	1500.0	11.20	1710.0	0.698
1287.0	0.472	1361.0	8.18	1510.0	10.62	1720.0	0.579
1290.5	0.542	1366.0	9.62	1520.0	10.03	1730.0	0.465
1293.0	0.584	1369.0	11.30	1530.0	9.39	1740.0	0.369
1296.5	0.550	1375.0	12.40	1540.0	8.52	1750.0	0.255

[a] The photodissociation process $O_2 + h\nu \rightarrow O\ (^3P) + O\ (^1D)$ associated with the Schumann absorption continuum between 1,350–1,750 (Å) occurs with a quantum yield of unity. Source of data: Watanabe (1958), Metzger and Cook (1964), Blake et al. (1966). Good agreement exists except in the region 1,390–1,500 (Å) where Watanabe's values are ~5% lower, but he alone provided comprehensive numerical values. Allowance has been made for the slight difference in the region of maximum absorption by taking appropriate averages

Table 9.17 Absorption cross sections (cm^2 $molecule^{-1}$) of carbon dioxide (1200 – 1950 [Å]) at 298 K[a]

λ (Å)	$10^{19}\,\sigma$	λ (Å)	$10^{19}\,\sigma$	λ (Å)	$10^{19}\,\sigma$	λ (Å)	$10^{19}\,\sigma$
1200	0.411	1313.1p	11.95	1424.2p	6.37	1620	1.21
1210	0.578	1316.0p	11.52	1429.0	4.91	1630	1.16
1215.6	0.742	1320.0	5.37	1435.2p	6.49	1640	0.801
1220	0.764	1324.2p	11.27	1440.0	5.40	1650	0.623
1230	1.07	1327.0p	9.09	1446.6p	6.67	1660	0.620
1236.0	1.20	1330.5	6.40	1454.0	5.51	1670	0.454
1238.8p	1.51	1334.8p	10.51	1457.2p	6.69	1680	0.362
1243.1p	1.81	1339.0p	8.66	1463.5	5.02	1690	0.268
1245.5	1.53	1342.5	5.92	1467.7p	6.61	1700	0.207
1248.9p	2.38	1347.6p	12.45	1471.5	5.22	1710	0.176
1252.7p	2.39	1354.5	5.49	1480.9p	6.16	1720	0.121
1255.0	2.07	1359.4p	9.60	1489.5	4.95	1730	0.0965
1259.7p	3.32	1365.5	5.62	1492.0p	5.66	1740	0.0753
1262.0p	3.47	1369.3p	6.70	1500	4.19	1750	0.0640
1265.5	2.30	1376.0	5.47	1510	4.13	1760	0.0455
1269.3p	4.43	1379.8p	6.85	1520	4.17	1770	0.0348
1272.2p	5.04	1385.1p	5.51	1530	4.21	1780	0.0274
1275.5	2.87	1388.0	4.90	1540	3.69	1790	0.0157
1280.1p	6.38	1393.4p	5.85	1550	2.99	1800	0.0145
1283.2p	6.01	1396.0	4.83	1560	2.82	1820	0.0100
1286.0	3.54	1402.7p	6.14	1570	2.87	1840	0.00576
1291.0p	8.95	1406.5	5.33	1580	2.09	1860	0.00325
1297.0	4.24	1411.7p	6.11	1590	1.85	1880	0.00166
1302.2p	11.53	1417.7p	5.79	1600	1.76	1900	0.00082
1309.0	5.01	1419.0	5.19	1610	1.52	1950	0.00021

[a] Cross sections at wavelengths of prominent bands (peaks, p) and deep valleys between peaks in the spectral region 1,236–1,500 (Å); in other regions the differences between peaks and valleys are slight. Sources of data: Lewis and Carver (1983), Yoshino et al. (1996a), above 1,700 (Å) from Shemansky (1972). Photodissociation leads to $CO(^1\Sigma^+) + O\ (^3P)$ ($\lambda \leq 2{,}275$ (Å)) and $CO(^1\Sigma^+) + O\ (^1D)$ ($\lambda \leq 1{,}671$ (Å)) with quantum yields of essentially unity in both cases (Welge 1974)

Table 9.18 Absorption cross sections (cm^2 $molecule^{-1}$) of water vapor (1142 – 1950 Å) at 298 K[a]

λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{19}\,\sigma$	λ (Å)	$10^{19}\,\sigma$
1142	1.67	1247.5	5.69	1319.5	62.8	1420	5.87
1151	4.57	1257.5	6.88	1328.5	42.7	1428	4.83
1161	2.08	1260	6.80	1334.5	49.8	1430	5.10
1173	8.55	1270	7.77	1340	41.9	1440	5.10
1180.5	2.53	1274.5	7.17	1350	35.4	1450	5.28
1192.5	11.52	1280	7.81	1360	23.8	1460	6.09
1205	3.53	1288	7.03	1370	19.1	1470	7.38
1215.6	14.39	1294	7.51	1380	16.6	1480	8.39
1220	18.22	1303	6.36	1390	11.5	1490	9.92
1230	2.57	1308	6.95	1400	8.58	1500	11.6
1239	13.01	1315.5	5.32	1410	7.51	1510	13.9

(continued)

Table 9.18 (continued)

λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{18}\,\sigma$	λ (Å)	$10^{19}\,\sigma$	λ (Å)	$10^{19}\,\sigma$
1520	15.9	1630	45.5	1740	33.5	1850	0.675
1530	18.7	1640	48.0	1750	30.4	1860	0.423
1540	20.1	1650	49.7	1760	27.4	1870	0.259
1550	23.3	1660	50.1	1770	23.1	1880	0.165
1560	26.1	1670	50.1	1780	18.3	1890	0.101
1570	29.0	1680	49.6	1790	13.3	1900	0.0630
1580	32.3	1690	48.6	1800	8.53	1910	0.0464
1590	35.1	1700	47.6	1810	5.14	1920	0.0258
1600	38.3	1710	45.5	1820	3.01	1930	0.0168
1610	40.1	1720	42.0	1830	1.78	1940	0.0095
1620	43.3	1730	38.2	1840	1.16	1950	0.0058

[a] Cross sections in the region ≤1,340 (Å) at wavelengths of peaks and valleys. Data sources: 1,142–1,820 (Å), Watanabe et al. (1953); in the region 1,340–1,450 (Å) averaged with data of Cheng et al. (2004); in the region 1,450–1,820 (Å) averaged with data of Yoshino et al. (1996b) and Chung et al. (2001); in the region beyond 1,830 (Å) averages of data from Cantrell et al. (1997) and Chung et al. (2001). The continuum above 1,450 (Å) leads to photodissociation: $H_2O + h\nu \rightarrow OH + O\ (^3P)$ ($\varphi \approx 1$). The second continuum at $\lambda < 1{,}450$ (Å) shows increasing band structure with strong diffuse bands below 1,250 (Å)

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9.5 Chemistry of the Ionosphere

Table 9.19 Characterization of the Ionosphere[a]

Region	Altitude (km)		Electron density (m^{-3})		Principal primary ion(s)	Major ion(s) observed
	Range	Peak	Day	Night		
Topside	350–1,000	–	10^{10}–10^{11}		O^+ diffusion	O^+, H^+
F2	200–400	300	5×10^{11}	1×10^{11}	O^+	O^+
F1	140–200	170	2×10^{11}	8×10^{8}	N_2^+, O^+	O^+, NO^+
E	90–140	110	1×10^{11}	2×10^{9}	O_2^+	O_2^+, NO^+
D	65–90	70–90	1×10^{9}	1×10^{8}	N_2^+, O_2^+, NO^+	Cluster ions[b]

[a] Numerical values are approximate. Peak altitudes and electron densities vary with solar activity and with geographic latitude. Source of data: Rees (1989)
[b] Major cluster ions in the D-region are $H_3O^+(H_2O)_n$, and negative ions such as HCO_3^- and NO_3^- (also partly hydrated)

Comments: The main region of ion production is the F1 region, where absorption of solar radiation in the EUV spectral range 25–90 nm maximizes. Atmospheric constituents in this altitude regime are mostly N_2 and atomic oxygen. Photoionization leads to N_2^+ and O^+ as primary ions, but N_2^+ is largely converted to O_2^+ and NO^+ by reactions with neutral species. In the F2 region atomic oxygen is the most abundant neutral species. Although the rate of ionization is lower, electron densities are higher, because ion-electron recombination of atomic ions is much less efficient than that of molecular ions; O^+ is preferentially destroyed in ion-molecule reactions. The peak F2 ion density occurs at an altitude where chemical and diffusive losses are nearly equal. The E layer is formed by absorption of solar radiation of wavelengths 1–25 nm and $\lambda > 90$ nm (primarily the Lyman β line at 102.6 nm) that reach deeper into the atmosphere. Whereas the strength of the F1 layer decreases strongly at night, the E-layer persists, despite rapid ion-electron recombination, owing to ionization by (resonance-scattered) radiation from high altitudes: the 58.4 and 30.4 nm lines scattered from helium are a source of O^+ in the F1 region, and Lyman β at 102.6 nm is a source of O_2^+ in the E region. The production of ions in the D region is due to X-rays <1 nm in addition to ionisation of NO by the Lyman α line, which penetrates to low altitudes through a window in the O_2 absorption spectrum.

Table 9.20 Rate coefficients of positive ion-neutral reactions relevant to the ionosphere[a]

Reaction	k	Reaction	k
$H^+ + O \rightarrow O^+ + H$	3.75 (−10)	$He^+ + CO \rightarrow C^+ + O + He$	1.6 (−9)
$H^+ + O_2 \rightarrow O_2^+ + H$	1.17 (−9)	$He^+ + H_2O \rightarrow H_2O^+ + He$	5.5 (−11)
$H^+ + NO \rightarrow NO^+ + H$	1.9 (−9)	$\rightarrow H^+ + OH + He$	1.85 (−10)
$H^+ + CO_2 \rightarrow CO_2^+ + H$	3.8 (−9)	$\rightarrow OH^+ + H + He$	2.6 (−10)
$H^+ + H_2O \rightarrow H_2O^+ + H$	8.2 (−9)	$He^+ + CH_4 \rightarrow CH_4^+ + He$	3.2 (−11)
$H^+ + CH_4 \rightarrow CH_3^+ + H_2$	3.4 (−9)	$\rightarrow CH_3^+ + H + He$	8.1 (−11)
$\rightarrow CH_4^+ + H$	7.47 (−10)	$\rightarrow CH_2^+ + H_2 + He$	8.4 (−10)
$H^+ + HCN \rightarrow HCN^+ + H$	1.1 (−8)	$\rightarrow CH^+ + H_2 + H + He$	2.4 (−10)
$H_2^+ + H \rightarrow H^+ + H_2$	6.4 (−10)	$\rightarrow H^+ + CH_3 + He$	4.4 (−10)
$H_2^+ + H_2 \rightarrow H_3^+ + H$	2.0 (−9)	$He^+ + HCN \rightarrow CH^+ + N + He$	6.9 (−10)
$H_2^+ + He \rightarrow HeH^+ + H$	1.35 (−10)	$\rightarrow CN^+ + H + He$	1.55 (−9)
$H_2^+ + CH_4 \rightarrow CH_3^+ + H_2 + H$	2.28 (−9)	$\rightarrow C^+ + NH + He$	8.3 (−10)
$\rightarrow CH_4^+ + H_2$	1.41 (−9)	$\rightarrow N^+ + CH + He$	2.3 (−10)
$H_2^+ + O_2 \rightarrow O_2^+ + H_2$	7.8 (−10)	$HeH^+ + H \rightarrow H_2^+ + He$	9.1 (−10)
$\rightarrow HO_2^+ + H$	1.92 (−10)	$HeH^+ + H_2 \rightarrow H_3^+ + He$	1.77 (−9)
$H_2^+ + N_2 \rightarrow N_2H^+ + H$	2.0 (−9)	$HeH^+ + N_2 \rightarrow N_2H^+ + He$	1.7 (−9)
$H_2^+ + CO_2 \rightarrow HCO_2^+ + H$	2.35 (−9)	$HeH^+ + O_2 \rightarrow HO_2^+ + He$	1.1 (−9)
$H_2^+ + CO \rightarrow HCO^+ + H$	2.9 (−9)	$N^+ + H_2 \rightarrow NH^+ + H$	5.0 (−10)
$H_3^+ + O \rightarrow OH^+ + H_2$	8.0 (−10)	$N^+ + H_2O \rightarrow H_2O^+ + N$	2.7 (−9)
$\rightarrow H_2O^+ + H$	overall	$N^+ + O_2 \rightarrow NO^+ + O$	2.3 (−10)
$H_3^+ + O_2 \rightarrow HO_2^+ + H_2$	6.7 (−10)	$\rightarrow O_2^+ + N$	3.1 (−10)
$H_3^+ + N \rightarrow NH^+ + H_2$	2.6 (−10)	$\rightarrow O^+ + NO$	4.6 (−11)
$\rightarrow NH_2^+ + H$	3.9 (−10)	$N^+ + NO \rightarrow N_2^+ + O$	8.3 (−11)
$H_3^+ + N_2 \rightarrow N_2H^+ + H_2$	1.86 (−9)	$\rightarrow NO^+ + N$	4.7 (−10)
$H_3^+ + NO \rightarrow HNO^+ + H_2$	1.25 (−9)	$N^+ + CO_2 \rightarrow CO^+ + NO$	2.0 (−10)
$H_3^+ + NO_2 \rightarrow NO^+ + OH + H_2$	7.0 (−10)	$\rightarrow CO_2^+ + N$	9.2 (−10)
$\rightarrow NO_2^+ + H + H_2$	7.0 (−12)	$N^+ + CO \rightarrow CO^+ + N$	4.93 (−10)
$H_3^+ + CO_2 \rightarrow HCO_2^+ + H_2$	2.5 (−9)	$\rightarrow NO^+ + C$	6.2 (−11)
$H_3^+ + CO \rightarrow HCO^+ + H_2$	1.74 (−9)	$\rightarrow C^+ + NO$	5.6 (−12)
$\rightarrow HOC^+ + H_2$	1.1 (−10)	$N^+ + CH_4 \rightarrow CH_4^+ + N$	5.75 (−11)
$H_3^+ + H_2O \rightarrow H_3O^+ + H_2$	5.3 (−9)	$\rightarrow CH_3^+ H + N$	5.75 (−10)
$H_3^+ + CH_4 \rightarrow CH_5^+ + H_2$	2.4 (−9)	$\rightarrow HCNH^+ + H_2$	4.14 (−10)
$H_3^+ + HCN \rightarrow HCNH^+ + H_2$	7.5 (−9)	$\rightarrow HCN^+ + H_2 + H$	1.15 (−10)
$He^+ + H_2 \rightarrow H^+ + H + He$	8.3 (−14)	$N^+ + HCN \rightarrow HCN^+ + N$	3.7 (−9)
$\rightarrow H_2^+ + He$	1.7 (−14)	$N_2^+ + H_2 \rightarrow N_2H^+ + H$	2.0 (−9)
$He^+ + O_2 \rightarrow O^+ + O + He$	9.7 (−10)	$N_2^+ + O \rightarrow O^+ + N_2$	1.0 (−11)
$\rightarrow O_2^+ + He$	3.0 (−11)	$\rightarrow NO^+ + N$	1.4 (−10)
$He^+ + N_2 \rightarrow N^+ + N + He$	7.8 (−10)	$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	5.0 (−11)
$\rightarrow N_2^+ + He$	5.2 (−10)	$N_2^+ + NO \rightarrow$ products	4.1 (−10)
$He^+ + NO \rightarrow N^+ + O + He$	1.35 (−9)	$N_2^+ + CO_2 \rightarrow CO_2^+ + N_2$	8.0 (−10)
$\rightarrow O^+ + N + He$	1.0 (−10)	$N_2^+ + CO \rightarrow CO^+ + N_2$	7.3 (−11)
$He^+ + CO_2 \rightarrow CO^+ + O + He$	7.8 (−10)	$N_2^+ + H_2O \rightarrow H_2O^+ + N_2$	1.9 (−9)
$\rightarrow CO_2^+ + He$	5.0 (−11)	$\rightarrow N_2H^+ + OH$	5.0 (−10)
$\rightarrow O^+ + CO + He$	1.4 (−10)	$N_2^+ + CH_4 \rightarrow CH_2^+ + H_2 + N_2$	1.0 (−10)
$\rightarrow C^+ + O_2^+ + He$	2.0 (−11)	$\rightarrow CH_3^+ + H + N_2$	1.04 (−9)

(continued)

Table 9.20 (continued)

Reaction	k	Reaction	k
$O^+ + H \rightarrow H^+ + O$	6.4 (−10)	$OH^+ + O_2 \rightarrow O_2^+ + OH$	3.8 (−10)
$O^+ + H_2 \rightarrow OH^+ + H$	1.62 (−9)	$OH^+ + NO \rightarrow NO^+ + OH$	8.15 (−10)
$O^+ + N_2 \rightarrow NO^+ + N$	1.2 (−12)	$OH^+ + NO_2 \rightarrow NO^+ + HO_2$	1.3 (−9)
$O^+ + O_2 \rightarrow O_2^+ + O$	2.1 (−11)	$\rightarrow NO_2^+ + OH$	overall
$O^+ + NO \rightarrow NO^+ + O$	8.0 (−13)	$OH^+ + CO_2 \rightarrow HCO_2^+ + O$	1.35 (−9)
$O^+ + NO_2 \rightarrow NO_2^+ + O$	1.6 (−9)	$OH^+ + CO \rightarrow HCO^+ + H$	8.4 (−10)
$O^+ + CO_2 \rightarrow O_2^+ + CO$	1.1 (−9)	$OH^+ + H_2O \rightarrow H_2O^+ + OH$	1.59 (−9)
$O^+ + H_2O \rightarrow H_2O^+ + O$	2.6 (−9)	$\rightarrow H_3O^+ + O$	1.3 (−9)
$O^+ + CH_4 \rightarrow CH_4^+ + O$	8.9 (−10)	$H_2O^+ + H_2 \rightarrow H_3O^+ + H$	7.6 (−10)
$\rightarrow CH_3^+ + OH$	1.1 (−10)	$H_2O^+ + O_2 \rightarrow O_2^+ + H_2O$	3.3 (−10)
$O^+ + HCN \rightarrow CO^+ + NH$	1.17 (−9)	$H_2O^+ + NO \rightarrow NO^+ + H_2O$	4.6 (−10)
$\rightarrow HCO^+ + N$	1.17 (−9)	$H_2O^+ + NO_2 \rightarrow NO_2^+ + H_2O$	1.3 (−9)
$\rightarrow NO^+ + CH$	1.17 (−9)	$H_2O^+ + CO \rightarrow HCO^+ + OH$	4.25 (−10)
$O_2^+ + N \rightarrow NO^+ + O$	1.5 (−10)	$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$	1.85 (−9)
$O_2^+ + NO \rightarrow O_2 + NO^+$	4.6 (−10)	$H_2O^+ + CH_4 \rightarrow H_3O^+ + CH_3$	1.12 (−9)
$O_2^+ + NO_2 \rightarrow O_2 + NO_2^+$	6.6 (−10)	$H_2O^+ + HCN \rightarrow H_3O^+ + CN$	2.1 (−9)
$OH^+ + H_2 \rightarrow H_2O^+ + H$	9.7 (−10)	$\rightarrow HCNH^+ + OH$	overall

[a] Powers of ten in parentheses, units of rate coefficients (cm^3 molecule^{-1} s^{-1}), $T \approx 300$ K. Source of data: Anicich (1993)

Table 9.21 Rate coefficients of positive ion reactions used in models of the ionosphere in the E and F regions [a]

Reaction	k (cm^3 molecule^{-1} s^{-1})	Reaction	k (cm^3 molecule^{-1} s^{-1})
$O^+(^4S) + N_2 \rightarrow N + NO^+$	1.533 (−12)	$O^+(^2P) + e^- \rightarrow O(^4S) + e^-$	1.7 (−7) $(300/T_e)^{0.5}$
	−5.92 (−13)$(T_f/300)$	$O^+(^2P) + O \rightarrow O(^4S) + O$	5.2 (−11)
	+ 8.6 (−14)$(T_f/300)^2$	$O^+(^2P) \rightarrow O^+(^2D) + h\nu$	0.173 s^{-1}
	$(T_f < 1{,}700$ K)	$O^+(^2P) \rightarrow O^+(^4S) + h\nu$	0.047 s^{-1}
$O^+(^2D) + N_2 \rightarrow O + N_2^+$	8.0 (−10)	$N_2^+ + O \rightarrow N_2 + O^+$	2.0 (−11)
$O^+(^2P) + N_2 \rightarrow O + N_2^+$	4.8 (−10)	$N_2^+ + O \rightarrow N + NO^+$	1.4 (−10)$(T_f/300)^{-0.44}$
$O^+(^4S) + N(^2D) \rightarrow O + N^+$	1.3 (−10)	$N_2^+ + O_2 \rightarrow N_2 + O_2^+$	5.0 (−11)$(T_f/300)^{-0.8}$
$O^+(^4S) + O_2 \rightarrow O + O_2^+$	2.82 (−11)	$N^+ + O \rightarrow N + O^+$	1.0 (−12)
	−7.74 (−12)$(T_f/300)$	$N^+ + O_2 \rightarrow O + NO^+$	2.6 (−10)
	+ 1.073 (−12)$(T_f/300)^2$	$N^+ + O_2 \rightarrow N + O_2^+$	3.1 (−10)
	− 5.17(−14)$(T_f/300)^3$	$O_2^+ + NO \rightarrow O_2 + NO^+$	4.4 (−10)
	+ 9.65 (−16) $(T_f/300)^4$	$O_2^+ + N \rightarrow O + NO^+$	1.2 (−10)
$O^+(^2D) + O_2 \rightarrow O + O_2^+$	7.0 (−10)	$O^+(^4S) + e^- \rightarrow O + h\nu$	4.0 (−12)$(300/T_e)^{0.7}$
$O^+(^2P) + O_2 \rightarrow O + O_2^+$	4.8 (−10)	$N_2^+ + e^- \rightarrow N + N$	1.8 (−7) $(300/T_e)^{0.39}$
$O^+(^2D) + O \rightarrow O(^4S) + O$	1.0 (−11)	$O_2^+ + e^- \rightarrow O + O$	1.95 (−7) $(300/T_e)^{0.7}$
$O^+(^2D) + e^- \rightarrow O(^4S) + e^-$	6.6 (−8) $(300/T_e)^{0.5}$	$NO^+ + e^- \rightarrow N + O$	4.0 (−7) $(300/T_e)^{0.9}$

[a] Powers of ten in parentheses; $T_f = (m_i T_n + m_n T_i)/(m_n + m_i)$, where T is temperature, m is mass and the subscripts i and n refer to ions and neutrals, respectively; T_e is electron temperature. Source of data: Buonsanto et al. (1992), Torr (1985)

Table 9.22 Ion reactions involving sodium and iron species, $T \approx 300$ K[a]

Reaction	k	Reaction	k
$N_2^+ + Na \rightarrow Na^+ + N_2$	1.3 (−9)	$O_2^+ + Fe \rightarrow Fe^+ + O_2$	1.1 (−9)
$O_2^+ + Na \rightarrow Na^+ + O_2$	2.9 (−9)	$NO^+ + Fe \rightarrow Fe^+ + NO$	9.2 (−10)
$NO^+ + Na \rightarrow Na^+ + NO$	8.0 (−10)	$H_2O^+ + Fe \rightarrow Fe^+ + H_2O$	1.5 (−9)
$H_2O^+ + Na \rightarrow Na^+ + H_2O$	6.2 (−9)	$Fe^+ + O_3 \rightarrow FeO^+ + O_2$	3.4 (−10)[c]
$Na^+ + N_2 + M \rightarrow Na^+ \cdot N_2 + M$	4.8 (−30)	$Fe^+ + O_2 + M \rightarrow FeO_2^+ + M$	1.7 (−29)
$Na^+ \cdot N_2 + X \rightarrow Na^+ \cdot X + N_2$	8.0 (−10)[b]	$Fe^+ + N_2 + M \rightarrow Fe^+ \cdot N_2 + M$	8.0 (−30)
$Na^+ \cdot N_2 + O \rightarrow NaO^+ + N_2$	6.0 (−10)	$Fe^+ \cdot N_2 + O \rightarrow FeO^+ + N_2$	7.0 (−10)
$NaO^+ + O \rightarrow Na^+ + O_2$	8.0 (−10)	$FeO_2^+ + O \rightarrow FeO^+ + O_2$	6.0 (−10)
$N_2^+ + Fe \rightarrow Fe^+ + N_2$	4.3 (−10)	$FeO^+ + O \rightarrow Fe^+ + O_2$	2.0 (−11)

[a]Powers of ten in parentheses, units of rate coefficients (cm^3 $molecule^{-1}$ s^{-1}) for bimolecular reactions and (cm^6 $molecule^{-2}$ s^{-1}) for termolecular reactions. Sources of data: Plane et al. (1999, 2003). Metals in the upper atmosphere arise from meteorite ablation

[b]X = CO_2 or H_2O

[c]The temperature dependence of the rate coefficient is $k = 7.6\ (-10)\ \exp(-241/T)$

Table 9.23 D-region positive ion chemistry and rate coefficients[a]

Reaction	k*	α	B
$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	5.1 (−10)		
$O_2^+ + O_2 + M \rightarrow O_4^+ + M$	4.0 (−30)	2.93	
$O_2^+ + N_2 + M \rightarrow N_2 \cdot O_2^+ + M$	1.0 (−30)	3.2	
$N_2 \cdot O_2^+ + O_2 \rightarrow O_4^+ + N_2$	5.0 (−10)		
$O_4^+ + M \rightarrow O_2^+ + O_2 + M$	2.8 (−5)	3.93	5,400
$N_2 \cdot O_2^+ + M \rightarrow O_2^+ + N_2 + M$	1.7 (−7)	4.2	2,700
$O_4^+ + O \rightarrow O_2^+ + O_3$	3.0 (−10)		
$O_4^+ + H_2O \rightarrow O_2^+ \cdot H_2O + O_2$	1.7 (−9)		
$O_2^+ \cdot H_2O + H_2O \rightarrow H_3O^+ \cdot OH + O_2$	9.0 (−10)		
$H_3O^+ \cdot OH + H_2O \rightarrow H^+(H_2O)_2 + OH$	2.0 (−9)		
$O_2^+ + H_2O_2 \rightarrow H_2O_2^+ + O_2$	1.5 (−9)		
$H_2O_2^+ + H_2O \rightarrow H_3O^+ + HO_2$	1.7 (−9)		
$NO^+ + N_2 + M \rightarrow N_2 \cdot NO^+ + M$	3.0 (−31)	4.7	
$NO^+ + CO_2 + M \rightarrow CO_2 \cdot NO^+ + M$	1.4 (−29)	4.7	
$N_2 \cdot NO^+ + M \rightarrow NO^+ + N_2 + M$	1.5 (−8)	5.3	2,093
$CO_2 \cdot NO^+ + M \rightarrow NO^+ + CO_2 + M$	6.2 (−7)	5.0	4,590
$NO^+ + H_2O + M \rightarrow NO^+ \cdot H_2O + M$	1.6 (−28)	4.7	
$CO_2 \cdot NO^+ + H_2O \rightarrow NO^+ \cdot H_2O + CO_2$	1.0 (−9)		
$N_2 \cdot NO^+ + CO_2 \rightarrow CO_2 \cdot NO^+ + N_2$	1.0 (−9)		
$NO^+ \cdot H_2O + N_2 + M \rightarrow NO^+ \cdot H_2O \cdot N_2 + M$	2.0 (−31)	4.4	
$NO^+ \cdot H_2O \cdot N_2 + M \rightarrow NO^+ \cdot H_2O + N_2 + M$	6.3 (−8)	5.4	2,150
$NO^+ \cdot H_2O + CO_2 + M \rightarrow NO^+ \cdot H_2O \cdot CO_2 + M$	7.0 (−30)	4.0	
$NO^+ \cdot H_2O \cdot CO_2 + M \rightarrow NO^+ \cdot H_2O + CO_2 + M$	3.8 (−6)	5.0	4,025
$NO^+ \cdot H_2O \cdot N_2 + CO_2 \rightarrow NO^+ \cdot H_2O \cdot CO_2 + N_2$	1.0 (−9)		
$NO^+ \cdot H_2O \cdot CO_2 + H_2O \rightarrow NO^+(H_2O)_2 + CO_2$	1.0 (−9)		
$NO^+ \cdot H_2O + H_2O + M \rightarrow NO^+(H_2O)_2 + M$	1.0 (−27)	4.7	
$NO^+(H_2O)_2 + N_2 + M \rightarrow NO^+(H_2O)_2 \cdot N_2 + M$	2.0 (−31)	4.4	
$NO^+(H_2O)_2 \cdot N_2 + M \rightarrow NO^+(H_2O)_2 + N_2 + M$	6.3 (−8)	5.4	1,800

(continued)

Table 9.23 (continued)

Reaction	k*	α	B
$NO^+(H_2O)_2 + CO_2 + M \rightarrow NO^+(H_2O)_2 \cdot CO_2 + M$	7.0 (−30)	3.0	
$NO^+(H_2O)_2 \cdot CO_2 + M \rightarrow NO^+(H_2O)_2 + CO_2 + M$	3.8 (−6)	5.0	3,335
$NO^+(H_2O)_2 \cdot N_2 + CO_2 \rightarrow NO^+(H_2O)_2 \cdot CO_2 + N_2$	1.0 (−9)		
$NO^+(H_2O)_2 \cdot CO_2 + H_2O \rightarrow NO^+(H_2O)_3 + CO_2$	1.0 (−9)		
$NO^+(H_2O)_2 + H_2O + M \rightarrow NO^+(H_2O)_3 + M$	9.0 (−28)	4.7	
$NO^+(H_2O)_3 + H_2O \rightarrow H^+(H_2O)_3 + HNO_2$	1.0 (−9)		
$H_3O^+ + N_2 + M \rightarrow H_3O^+ \cdot N_2 + M$	3.5 (−31)	4.0	
$H_3O^+ \cdot N_2 + M \rightarrow H_3O^+ + N_2 + M$	1.0 (−8)	5.4	2,800
$H_3O^+ + CO_2 + M \rightarrow H_3O^+ \cdot CO_2 + M$	8.5 (−28)	4.0	
$H_3O^+ \cdot CO_2 + M \rightarrow H_3O^+ + CO_2 + M$	5.5 (−3)	5.0	7,700
$H_3O^+ \cdot N_2 + CO_2 \rightarrow H_3O^+ \cdot CO_2 + N_2$	1.0 (−9)		
$H_3O^+ \cdot CO_2 + H_2O \rightarrow H^+(H_2O)_2 + CO_2$	1.0 (−9)		
$H_3O^+ + H_2O + M \rightarrow H^+(H_2O)_2 + M$	4.6 (−27)	4.0	
$H^+(H_2O)_2 + M \rightarrow H_3O^+ + H_2O + M$	2.5 (−2)	5.0	15,900
$H^+(H_2O)_2 + N_2 + M \rightarrow H^+(H_2O)_2 \cdot N_2 + M$	3.5 (−31)	4.0	
$H^+(H_2O)_2 \cdot N_2 + M \rightarrow H^+(H_2O)_2 + N_2 + M$	1.2 (−8)	5.4	2,700
$H^+(H_2O)_2 + CO_2 + M \rightarrow H^+(H_2O)_2 \cdot CO_2 + M$	8.5 (−28)	4.0	
$H^+(H_2O)_2 \cdot CO_2 + M \rightarrow H^+(H_2O)_2 + CO_2 + M$	1.0 (−3)	5.0	6,200
$H^+(H_2O)_2 \cdot N_2 + CO_2 \rightarrow H^+(H_2O)_2 \cdot CO_2 + N_2$	1.0 (−9)		
$H^+(H_2O)_2 \cdot CO_2 + H_2O \rightarrow H^+(H_2O)_3 + CO_2$	1.0 (−9)		
$H^+(H_2O)_2 + H_2O + M \rightarrow H^+(H_2O)_3 + M$	8.6 (−27)	7.5	
$H^+(H_2O)_3 + M \rightarrow H^+(H_2O)_2 + H_2O + M$	1.2 (−2)	8.5	9,800
$H^+(H_2O)_3 + H_2O + M \rightarrow H^+(H_2O)_4 + M$	3.6 (−27)	8.1	
$H^+(H_2O)_4 + M \rightarrow H^+(H_2O)_3 + H_2O + M$	1.5 (−1)	9.1	9,000
$H^+(H_2O)_4 + H_2O + M \rightarrow H^+(H_2O)_5 + M$	4.6 (−28)	14.0	
$H^+(H_2O)_5 + M \rightarrow H^+(H_2O)_4 + H_2O + M$	1.7 (−3)	15.0	6,400
$H^+(H_2O)_5 + H_2O + M \rightarrow H^+(H_2O)_6 + M$	5.8 (−29)	15.3	
$H^+(H_2O)_6 + M \rightarrow H^+(H_2O)_5 + H_2O + M$	4.0 (−3)	16.3	5,800
$H^+(H_2O)_6 + H_2O + M \rightarrow H^+(H_2O)_7 + M$	9.0 (−28)	15.3	
$H^+(H_2O)_7 + M \rightarrow H^+(H_2O)_6 + H_2O + M$	1.3 (−2)	16.3	5,400

[a]Powers of ten in parentheses, $M = N_2$ or O_2, $k = k^*(300/T)^{\alpha} \exp(-B/T)$ in units of (cm^3 $molecule^{-1}$ s^{-1}) for bimolecular reactions and (cm^6 $molecule^{-2}$ s^{-1}) for termolecular reactions. Source: Kopp (1996)

Table 9.24 D-region negative ion chemistry and rate coefficients[a]

Reaction	k	Reaction	k
$O_2 + O_2 + e^- \rightarrow O_2^- + O_2$	4.0 (−30)	$O^- + O_2(^1\Delta_g) \rightarrow O_3 + e^-$	3.0 (−10)
$O_2 + N_2 + e^- \rightarrow O_2^- + N_2$	1.0 (−31)	$O^- + M \rightarrow O + e^- + M$	1.2 (−12)
$O_3 + e^- \rightarrow O^- + O_2$	9.1 (−12)	$O^- + CH_4 \rightarrow OH^- + CH_3$	1.0 (−10)
$O^- + O_3 \rightarrow O_3^- + O$	8.0 (−10)	$O^- + HCl \rightarrow Cl^- + OH$	2.0 (−9)
$O^- + CO_2 + M \rightarrow CO_3^- + M$	2.8 (−28)	$O^- + H_2 \rightarrow OH^- + H$	3.2 (−11)
$O^- + NO_2 \rightarrow NO_2^- + O$	1.0 (−9)	$O^- + H_2 \rightarrow H_2O + e^-$	5.8 (−10)
$O^- + O \rightarrow O_2 + e^-$	1.9 (−10)	$Cl^- + O_3 \rightarrow ClO^- + O_2$	5.0 (−13)
$O^- + NO \rightarrow NO_2 + e^-$	3.1 (−10)	$Cl^- + NO_2 \rightarrow NO_2^- + Cl$	6.0 (−12)
$O^- + CO \rightarrow CO_2 + e^-$	5.5 (−10)	$Cl^- + H \rightarrow HCl + e^-$	9.6 (−10)

(continued)

Table 9.24 (continued)

Reaction	k	Reaction	k
$Cl^- + HCl + M \rightarrow Cl^-(HCl) + M$	1.0 (−27)	$NO_2^- + HCl \rightarrow Cl^- + HNO_2$	1.4 (−9)
$Cl^- + H_2O + M \rightarrow Cl^-(H_2O) + M$	2.0 (−29)	$NO_3^- + O_3 \rightarrow NO_2^- + 2\ O_2$	1.0 (−13)
$Cl^- + CO_2 + M \rightarrow Cl^-(CO_2) + M$	6.0 (−29)	$NO_3^- + NO \rightarrow NO_2^- + NO_2$	1.0 (−12)
$Cl^- + HNO_3 \rightarrow NO_3^- + HCl$	1.6 (−9)	$NO_3^- + HCl \rightarrow Cl^- + HNO_3$	1.0 (−12)
$O_2^- + O \rightarrow O^- + O_2$	1.5 (−10)	$NO_3^- + H_2O + M \rightarrow NO_3^-(H_2O) + M$	1.6 (−28)
$O_2^- + O \rightarrow O_3 + e^-$	1.5 (−10)	$O_2^- + NO_2 \rightarrow NO_2^- + O_2$	7.0 (−10)
$O_2^- + O_2\ (^1\Delta_g) \rightarrow e^- + 2\ O_2$	2.0 (−10)	$NO_3^-(H_2O) + M \rightarrow NO_3^- + H_2O + M$	2.4 (−4)
$O_2^- + O_3 \rightarrow O_3^- + O_2$	7.8 (−10)	$O_4^- + O \rightarrow O_3^- + O_2$	4.0 (−10)
$O_2^- + HCl \rightarrow Cl^- + HO_2$	1.6 (−9)	$O_4^- + NO \rightarrow NO_3^- + O_2$	2.5 (−10)
$O_2^- + O_2 + M \rightarrow O_4^- + M$	3.4 (−31)	$O_4^- + CO \rightarrow CO_3^- + O_2$	2.0 (−11)
$O_2^- + CO_2 + M \rightarrow CO_4^- + M$	4.7 (−29)	$O_4^- + CO_2 \rightarrow CO_4^- + O_2$	4.3 (−10)
$O_2^- + H_2O + M \rightarrow O_2^-(H_2O) + M$	2.2 (−28)	$O_4^- + H_2O \rightarrow O_2^-(H_2O) + O_2$	1.0 (−10)
$OH^- + O \rightarrow HO_2 + e^-$	2.0 (−10)	$CO_3^- + O \rightarrow O_2^- + CO_2$	1.1 (−10)
$OH^- + O_3 \rightarrow O_3^- + OH$	9.0 (−10)	$CO_3^- + H \rightarrow OH^- + CO_2$	1.7 (−10)
$OH^- + NO_2 \rightarrow NO_2^- + OH$	1.1 (−9)	$CO_3^- + NO \rightarrow NO_2^- + CO_2$	1.0 (−10)
$OH^- + H \rightarrow H_2O + e^-$	1.4 (−9)	$CO_3^- + NO_2 \rightarrow NO_3^- + CO_2$	2.0 (−10)
$OH^- + HCl \rightarrow Cl^- + H_2O$	1.0 (−10)	$CO_3^- + HNO3 \rightarrow NO_3^- + HCO_3$	8.0 (−10)
$OH^- + CH_4 \rightarrow CH_3^- + H_2O$	1.0 (−12)	$CO_3^- + HCl \rightarrow Cl^- + OH + CO_2$	3.0 (−11)
$OH^- + CO_2 + M \rightarrow HCO_3^- + M$	7.6 (−28)	$CO_3^- + H_2O + M \rightarrow CO_3^-(H_2O) + M$	1.0 (−28)
$OH^- + H_2O + M \rightarrow OH^-(H_2O) + M$	2.5 (−28)	$CO_3^-(H_2O) + NO \rightarrow NO_2^- + CO_2 + H_2O$	7.0 (−12)
$ClO^- + O_3 \rightarrow Cl^- + 2\ O_2$	6.0 (−11)	$CO_3^-(H_2O) + NO_2 \rightarrow NO_3^- + CO_2 + H_2O$	1.5 (−10)
$ClO^- + O_3 \rightarrow O_3^- + ClO$	1.0 (−11)	$CO_4^- + O \rightarrow CO_3^- + O_2$	1.4 (−10)
$O_3^- + O \rightarrow O_2^- + O_2$	2.5 (−10)	$CO_4^- + H \rightarrow CO_3^- + OH$	2.2 (−10)
$O_3^- + O \rightarrow 2\ O_2 + e^-$	1.0 (−10)	$CO_4^- + O_3 \rightarrow O_3^- + CO_2 + O_2$	1.3 (−10)
$O_3^- + O_3 \rightarrow 3\ O_2 + e^-$	1.0 (−10)	$CO_4^- + NO \rightarrow NO_3^- + CO_2$	4.8 (−11)
$O_3^- + H \rightarrow OH^- + O_2$	8.4 (−10)	$CO_4^- + H_2O \rightarrow O_2^-\ (H_2O) + CO_2$	2.5 (−10)
$O_3^- + CO_2 \rightarrow CO_3^- + O_2$	5.5 (−10)	$CO_4^- + HCl \rightarrow ClHO_2^- + CO_2$	1.2 (−9)
$O_3^- + NO_2 \rightarrow NO_3^- + O_2$	2.8 (−10)	$O_2^-(H_2O) + CO_2 \rightarrow CO_4^- + H_2O$	5.8 (−10)
$O_3^- + NO \rightarrow NO_3^- + O$	2.6 (−12)	$O_2^-(H_2O) + NO \rightarrow NO_3^- + H_2O$	2.0 (−10)
$O_3^- + H_2O + M \rightarrow O_3^-(H_2O) + M$	2.7 (−28)	$O_2^-(H_2O) + O_3 \rightarrow O_3^- + O_2 + H_2O$	8.0 (−10)
$NO_2^- + O_3 \rightarrow NO_3^- + O_2$	1.2 (−10)	$NO_3^-(H_2O) + M \rightarrow NO_3^- + H_2O + M$	6.5 (−15)[b]
$NO_2^- + H \rightarrow OH^- + NO$	3.0 (−10)		
$NO_2^- + HNO_3 \rightarrow NO_3^- + HNO_2$	1.6 (−9)		

[a]Powers of ten in parentheses, k at 300 K in unit of (cm^3 $molecule^{-1}$ s^{-1}) for bimolecular reactions and (cm^6 $molecule^{-2}$ s^{-1}) for termolecular reactions. Source: Kopp (1996)
[b]Temperature dependence: $k = 2.4\ (-10)\ \exp\ (-7{,}300/T)$

Table 9.25 Photodetachment and photodissociation coefficients (s^{-1}) of negative ions[a]

Reaction	k (s^{-1})	Reaction	k (s^{-1})
$O^- + h\nu \rightarrow O + e^-$	1.4	$NO_2^- + h\nu \rightarrow NO_2 + e^-$	8.0 (−4)
$O_2^- + h\nu \rightarrow O_2 + e^-$	3.8 (−1)	$NO_3^- + h\nu \rightarrow NO_2 + e^-$	5.2 (−2)
$O_3^- + h\nu \rightarrow O_2 + O^-$	4.7 (−1)	$CO_3^- + h\nu \rightarrow CO_2 + O^-$	1.5 (−1)
$O_3^- + h\nu \rightarrow O_3 + e^-$	4.7 (−2)	$CO_3^- + h\nu \rightarrow CO_3 + e^-$	2.2 (−2)
$O_4^- + h\nu \rightarrow O_2 + O_2^-$	2.4 (−1)	$CO_4^- + h\nu \rightarrow CO_2 + O_2^-$	6.2 (−3)
$OH^- + h\nu \rightarrow OH + e^-$	1.1		

[a]Powers of ten in parentheses; Source of data: Kopp (1996)

Table 9.26 Electron-ion recombination rate coefficients[a]

Reaction	k^*	α	Reaction	k^*	α
$O_2^+ + e^- \rightarrow O + O$	1.9 (−7)	0.7	$NO^+(H_2O)_2CO_2 + e^-$	2 (−6)	
$NO^+ + e^- \rightarrow N + O$	4.2 (−7)	0.9	$H_3O^+ OH + e^-$	1.5 (−6)	
$H_2O_2^+ + e^-$	6.0 (−7)	0.5	$H_3O + e^-$	6.3 (−7)	0.5
$O_4^+ + e^-$	4.2 (−6)	0.5	$H_3O^+(H_2O) + e^-$	2.5 (−6)	
$O_2^+(H_2O) + e^-$	2 (−6)		$H_3O^+(H_2O)_2 + e^-$	3 (−6)	
$NO^+(N_2) + e^-$	1.4 (−6)	0.4	$H_3O^+(H_2O)_3 + e^-$	3.6 (−6)	
$NO^+(CO_2) + e^-$	1.5 (−6)		$H_3O^+(H_2O)_4 + e^-$	5 (−6)	
$NO^+(H_2O) + e^-$	1.5 (−6)		$H_3O^+(H_2O)_5 + e^-$	5 (−6)	
$NO^+(H_2O)_2 + e^-$	2 (−6)		$H_3O^+(N_2) + e^-$	1.5 (−6)	
$NO^+(H_2O)_3 + e^-$	2 (−6)		$H_3O^+(CO_2) + e^-$	2 (−6)	
$NO^+(H_2O)N_2 + e^-$	2 (−6)		$H_3O^+(H_2O)N_2 + e^-$	1.5 (−6)	
$NO^+(H_2O)CO_2 + e^-$	2 (−6)		$H_3O^+(H_2O)CO_2 + e^-$	3 (−6)	

[a]Powers of ten in parentheses, $k = k^* \ (300/T_e)^\alpha$ in units of (cm^3 $molecule^{-1}$ s^{-1}). Only measured temperature exponents are given. For other reactions the theoretical value $\alpha = 0.5$ may be applied. Source of data: Kopp (1996)

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9.6 Airglow Phenomena and Spectroscopy

Spectral emissions in the upper atmosphere arise from fluorescence in the presence of solar radiation and from chemiluminescence at all times. Rayleigh scattering during the day precludes the observation of emissions from the ground, although individual lines may be detected by interferometers at very high resolution. The nightglow spectrum observable from the ground is limited to the near UV, visible and near infrared wavelength region. The dayglow spectrum and the ultraviolet part of the nightglow can be observed with instruments on rockets and satellites. Aurorae are produced by interaction with atmospheric constituents of energetic electrons and protons precipitating from the magnetosphere into the upper atmosphere. Auroral spectra resemble those of the airglow but are more intense and superimposed on the regular airglow emissions (day and night).

Table 9.27 Summary of spectra observed in the airglow and aurorae[a]

Species	Transition	Wavelength or range[a] (nm)	Altitude[a] (km)	Excitation processes[b]
Nightglow				
O_2	a $^1\Delta_g$ – X $^3\Sigma_g^-$	1270.4, 1583.6	85–100	$2\,O + M \rightarrow O_2^* + M$
O_2	b $^1\Sigma_g^+$ – X $^3\Sigma_g^-$	761.9, 864.5	60–95	$2\,O + M \rightarrow O_2^* + M$
O_2	A $^3\Sigma_u^+$ – X $^3\Sigma_g^-$	255–390	85–105	$2\,O + M \rightarrow O_2^* + M$
O_2	A′ $^3\Delta_u$ – a $^1\Delta_g$	330–430	85–105	$2\,O + M \rightarrow O_2^* + M$
OH	X $^2\Pi_i$ ($\upsilon' \leq 9$)	550–2,000	56–100	$H + O_3 \rightarrow OH^* + O_2$
NO_2	$\tilde{A}(^2B_1)$ – $X(^2A_1)$	400–1,400	85–110	$O + NO \rightarrow NO_2^*$
NO	A $^2\Sigma^+$ – X $^2\Pi_r$	225–245	80–150	$N + O \rightarrow NO^*$
	C $^2\Pi_r$ – X $^2\Pi_r$	190–230	80–150	$N + O \rightarrow NO^*$
O	($^1D_2$) – ($^3P_{2,1}$)	630.0, 636.4	> 110	$O_2^+ + e \rightarrow O^* + O$
	($^1S_0$) – ($^1D_2$)	557.7	150–250	$O_2^+ + e \rightarrow O^* + O$
			85–110	$2\,O + M \rightarrow O_2\dagger + M$
				$O_2\dagger + O \rightarrow O^* + O_2$
Na	Na($^2P_{1/2,\,3/2}$)–Na(^2S)	589.6, 589.0	85–110	$Na + O_3 \rightarrow NaO + O_2$
				$NaO + O \rightarrow Na^* + O_2$
Dayglow[c]				
O_2	a $^1\Delta_g$ – X $^3\Sigma_g^-$	1270.4, 1583.6	50	$O_3 + h\nu \rightarrow O\,(^1D) + O_2^*$
NO	A $^2\Sigma^+$ – X $^2\Pi_r$	200–280	>110	resonance fluorescence
	C $^2\Pi_r$ – X $^2\Pi_r$	190–230	>110	resonance fluorescence
N_2	a $^1\Pi_g$ – X $^1\Sigma_u^+$	127–170	> 110	$N_2 + e_p \rightarrow N_2^* + e$
	A $^3\Sigma_u^+$ – X $^1\Sigma_u^+$	260–400	> 110	$N_2 + e_p \rightarrow N_2^* + e$
	C $^3\Pi_u$ – B $^3\Pi_g$	290–405	> 110	$N_2 + e_p \rightarrow N_2^* + e$
N_2^+	B $^2\Sigma_u^+$ – X $^2\Sigma_u^+$	358–427	> 110	resonance fluorescence
Aurora[d]				
N_2	B $^3\Pi_g$ – A $^3\Sigma_u^+$	530–950	> 85	$N_2 + e \rightarrow N_2^* + e$
N_2^+	A $^2\Pi_u$ – X $^2\Sigma_u^+$	550–1,100	> 85	$N_2 + e \rightarrow N_2^{+*} + e$
O_2^+	b $^4\Sigma_g^-$ – a $^4\Pi_u$	500–890	> 85	$O_2 + e \rightarrow O_2^{+*} + e$

[a]Wavelength and altitude ranges are approximate. See the following tables for spectroscopic details. The data are assembled from the reviews of McEwan and Phillips (1975) and Rees (1989)

[b]An asterisk indicates the exited atom or molecule responsible for the observed spectroscopic transition, a dagger indicates an energy-rich intermediate species (see comments), e_p denotes a photoelectron produced with excess kinetic energy, e is a thermal electron

[c]Emissions observed at night continue during the day

[d]These emissions are observed in addition to the above spectra

Comments:

(a) The four band systems of O_2 observed in the nightglow arise from the association of oxygen atoms. The very weakly bound $^5\Pi_g$ state of oxygen has been implicated as an intermediate in populating the excited states involved in the emissions. The $^5\Pi_g$ state may also be responsible for the energy transfer to atomic oxygen to form O ($^1S_0$) in the 85–110 km altitude region (Wraight 1982).

(b) Only the $\upsilon' = 0$ progressions appear in the atmospheric (a $^1\Delta_g$ – X $^3\Sigma_g^-$) and the infrared atmospheric (b $^1\Sigma_g^+$ – X $^3\Sigma_g^-$) band systems.

(c) The nightglow spectrum in the wavelength range 250–380 nm is dominated by the Herzberg I band ($A\ ^3\Sigma_u^+ - X\ ^3\Sigma_g^-$) system (except for the O ($^1S_0$) – ($^3P_1$) line at 297.2 nm, which parallels the O ($^1S_0$) – ($^1D_2$) transition at 557.7 nm). The relative population of the $A\ ^3\Sigma_u^+$ state favors the $\upsilon' = 4, 5, 6$ levels. Higher levels are mostly quenched by collisions.

(d) In the spectral region below 170 nm dayglow and aurora features are dominated by lines due to excited oxygen and nitrogen atoms as well as the strong Lyman alpha hydrogen line at 121.6 nm, in addition to the Lyman-Birge-Hopfield ($a\ ^1\Pi_g \rightarrow X\ ^1\Sigma_g^+$) band system of nitrogen.

(e) The N_2^+ ($B\ ^2\Sigma_u^+ - X\ ^2\Sigma_g^+$) transition shows primarily the 1–0, 0–0, and 0–1 bands.

Table 9.28 Spectral lines of oxygen and nitrogen atoms observed in the airglow and aurora (wavelengths and energy levels)[a]

Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})		Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})	
Oxygen (OI)					135.851	$^5S^0_2$	73768.200
92.2	92.201	$^1F^0_3$	124326.791			$^3P_1$	158.265
		$^1D_2$	15867.862	164.1	164.131	$^3S^0_1$	76794.978
102.7	102.576	$^3D^0_3$	97488.538			$^1D_2$	15867.862
		$^3P_2$	0.00	297.2	297.228	$^1S_0$	33792.583
	102.576	$^3D^0_2$	97488.448			$^3P_1$	158.265
		$^3P_2$	0.00	394.7	394.729	$^5P_3$	120809.848
	102.743	$^3D^0_2$	97488.448			$^5S^0_2$	95476.728
		$^3P_1$	158.265		394.748	$^5P_2$	120808.629
	102.743	$^3D^0_1$	97488.378			$^5S^0_2$	95476.728
		$^3P_1$	158.265		394.759	$^5P_2$	120807.923
	102.816	$^3D^0_1$	97488.378			$^5S^0_2$	95476.728
		$^3P_0$	226.977	557.7	557.735	$^1S_0$	33792.583
115.2	115.215	$^1D^0_2$	102661.966			$^1D_2$	15867.862
		$^1D_2$	15867.862	630.0	630.030	$^1D_2$	15867.862
130.4	130.217	$^3S^0_1$	76794.978			$^3P_2$	0.00
		$^3P_2$	0.00		636.378	$^1D_2$	15867.862
	130.486	$^3S^0_1$	76794.978			$^3P_1$	158.265
		$^3P_1$	158.265	777.4	777.194	$^5P_3$	86631.454
	130.603	$^3S^0_1$	76794.978			$^5S^0_2$	73768.200
		$^3P_0$	226.977		777.417	$^5P_2$	86627.778
135.6	135.559	$^5S^0_2$	73768.200			$^5S^0_2$	73768.200
		$^3P_2$	0.00		777.539	$^5P_1$	86625.757
135.6	135.851	$^5S^0_2$	73768.200			$^5S^0_2$	73768.200
		$^3P_1$	158.265	844.6	844.625	$^3P_0$	88631.303
	135.559	$^5S^0_2$	73768.200			$^3S^0_1$	76794.978
		$^3P_2$	0.00		844.636	$^3P_2$	88631.146
						$^3S^0_1$	76794.978

(continued)

Table 9.28 (continued)

Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})		Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})	
	844.676	$^3P_1$	88630.587		67.295	$^2P_{3/2}$	189068.514
		$^3S^0_1$	76794.978			$^2P^0_{1/2}$	40470.00
Singly ionized oxygen (OII)				71.8	71.846	$^2D_{3/2}$	165996.50
43.0	43.018	$^4P_{5/2}$	232462.724			$^2D^0_{5/2}$	26810.55
	43.004	$^4P_{3/2}$	232535.949		71.856	$^2D_{3/2}$	165996.50
		$^4S^0_{3/2}$	0.00			$^2D^0_{3/2}$	26830.57
	42.992	$^4P_{1/2}$	232602.492		71.861	$^2D_{5/2}$	165988.46
		$^4S_{3/2}$	0.00			$^2D^0_{3/2}$	26830.57
48.4	48.376	$^2P_{1/2}$	233544.59	79.7	79.668	$^2D_{5/2}$	165988.46
		$^2D^0_{3/2}$	26830.57			$^2P^0_{3/2}$	40468.01
	48.403	$^2P_{3/2}$	233430.53		79.664	$^2D_{3/2}$	165996.50
		$^2D^0_{3/2}$	26830.57			$^2P^0_{1/2}$	40470.00
53.9	53.985	$^4P_{1/2}$	185235.281		79.663	$^2D_{3/2}$	165996.50
	53.945	$^4P_{3/2}$	185340.577			$^2P^0_{1/2}$	40468.01
	53.909	$^4P_{5/2}$	185499.124	83.4	83.447	$^4P_{5/2}$	119837.21
		$^4S^0_{3/2}$	0.00			$^4S^0_{3/2}$	0.00
55.5	55.512	$^2D_{5/2}$	206971.68		83.333	$^4P_{3/2}$	120000.43
		$^2D^0_{3/2}$	26830.57			$^4S^0_{3/2}$	0.00
55.5	55.512	$^2D_{3/2}$	206972.72		83.276	$^4P_{1/2}$	120082.86
		$^2P^0_{3/2}$	26830.57			$^4S^0_{3/2}$	0.00
	55.505	$^2D_{3/2}$	206972.72	247.0	247.022	$^2P^0_{1/2}$	40470.00
		$^2D^0_{5/2}$	26810.55			$^4S^0_{3/2}$	0.00
60.1	60.059	$^2D_{5/2}$	206971.68		247.034	$^2P^0_{3/2}$	40468.01
		$^2P^0_{3/2}$	40468.01			$^4S^0_{3/2}$	0.00
	60.058	$^2D_{3/2}$	206972.72	372.6	372.604	$^2D^0_{3/2}$	26830.57
		$^2P^0_{3/2}$	40468.01			$^4S^0_{3/2}$	0.00
	60.059	$^2D_{3/2}$	206972.72		372.882	$^2D^0_{5/2}$	26810.55
		$^2P^0_{1/2}$	40470.00			$^4S^0_{3/2}$	0.00
61.6	61.706	$^2P_{1/2}$	188888.543	374.9	371.275	$^4S^0_{3/2}$	212161.881
		$^2D^0_{3/2}$	26830.57			$^4P_{1/2}$	185235.281
	61.638	$^2P_{3/2}$	189068.514		372.733	$^4S^0_{3/2}$	212161.881
		$^2D^0_{3/2}$	26830.57			$^4P_{3/2}$	185340.577
	61.630	$^2P_{3/2}$	189068.514		374.949	$^4S^0_{3/2}$	212161.881
		$^2D^0_{5/2}$	26810.58			$^4P_{5/2}$	185499.124
64.4	64.415	$^2S_{1/2}$	195710.47	434.9	431.715	$^4P^0_{3/2}$	208392.258
		$^2P^0_{3/2}$	40468.01			$^4P_{1/2}$	185235.281
	64.416	$^2S_{1/2}$	195710.47		431.963	$^4P^0_{5/2}$	208484.202
		$^2P^0_{1/2}$	40470.00			$^4P_{3/2}$	185340.577
67.3	67.376	$^2P_{1/2}$	188888.543		432.676	$^4P^0_{1/2}$	208346.104
		$^2P^0_{3/2}$	40468.01			$^4P_{1/2}$	185235.281
	67.377	$^2P_{1/2}$	188888.543		434.558	$^4P^0_{1/2}$	208346.104
		$^2P^0_{1/2}$	40470.00			$^4P_{3/2}$	185340.577
	67.295	$^2P_{3/2}$	189068.514		434.945	$^4P^0_{5/2}$	208484.202
		$^2P^0_{3/2}$	40468.01			$^4P_{5/2}$	185499.124

(continued)

Table 9.28 (continued)

Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})		Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})	
	436.692	$^4P^0_{3/2}$	208392.258		116.854	$^2F_{5/2}$	104810.360
		$^4P_{5/2}$	185499.124			$^2D^0_{5/2}$	19233.177
441.6	441.491	$^2D^0_{5/2}$	211712.732	120.0	119.955	$^4P_{5/2}$	83364.620
		$^2P_{3/2}$	189068.514			$^4S_{3/2}$	0.00
	441.600	$^2D^0_{3/2}$	211527.117	120.0	120.022	$^4P_{3/2}$	83317.830
		$^2P_{1/2}$	188888.543			$^4S_{3/2}$	0.00
	445.238	$^2D^0_{3/2}$	211527.117		120.710	$^4P_{1/2}$	83284.070
		$^2P_{3/2}$	189068.514			$^4S_{3/2}$	0.00
464.9	463.885	$^4D^0_{3/2}$	206786.286	124.3	124.318	$^2D_{5/2}$	99663.427
		$^4P_{1/2}$	185235.281			$^2D^0_{5/2}$	19224.464
464.9	464.181	$^4D^0_{5/2}$	206877.865		124.317	$^2D_{3/2}$	99663.912
		$^4P_{3/2}$	185340.577			$^2D^0_{5/2}$	19224.464
	464.914	$^4D^0_{7/2}$	207002.482		124.331	$^2D_{3/2}$	99663.912
		$^4P_{5/2}$	185499.124			$^2D^0_{3/2}$	19233.177
	465.084	$^4D^0_{1/2}$	206730.762		124.331	$^2D_{5/2}$	99663.427
		$^4P_{1/2}$	185235.281			$^2D^0_{3/2}$	19233.177
	466.164	$^4D^0_{3/2}$	206786.286	149.3	149.263	$^2P_{3/2}$	86220.510
		$^4P_{3/2}$	185340.577			$^2D^0_{5/2}$	19224.464
464.9	467.623	$^4D^0_{5/2}$	206877.865		149.282	$^2P_{3/2}$	86220.510
		$^4P_{5/2}$	185499.124			$^2D^0_{3/2}$	19233.177
732.0	732.969	$^2P^0_{1/2}$	40470.00		149.468	$^2P_{1/2}$	86137.350
		$^2D^0_{3/2}$	26830.57			$^2D^0_{3/2}$	19233.177
	733.074	$^2P^0_{3/2}$	40468.01	174.3	174.273	$^2P_{3/2}$	86220.510
		$^2D^0_{3/2}$	26830.57			$^2P^0_{3/2}$	28839.306
	732.000	$^2P^0_{3/2}$	40468.01	174.3	174.273	$^2P_{3/2}$	86220.510
		$^2D^0_{5/2}$	26810.55			$^2P^0_{3/2}$	28839.306
Nitrogen (NI)					174.526	$^2P_{1/2}$	86137.350
96.5	96.504	$^4P_{1/2}$	103622.51			$^2P^0_{3/2}$	28839.306
		$^4S_{3/2}$	0.00		174.524	$^2P_{1/2}$	86137.350
	96.463	$^4P_{3/2}$	103667.61			$^2P^0_{1/2}$	28838.920
		$^4S_{3/2}$	0.00	346.6	346.650	$^2P^0_{3/2}$	28839.306
	96.399	$^4P_{5/2}$	103735.48			$^4S_{3/2}$	0.00
		$^4S_{3/2}$	0.00		346.655	$^2P^0_{1/2}$	28838.920
113.4	113.417	$^4P_{1/2}$	88170.570			$^4S_{3/2}$	0.00
		$^4S_{3/2}$	0.00	520.0	519.790	$^2D^0_{3/2}$	19233.177
	113.442	$^4P_{3/2}$	88151.170			$^4S_{3/2}$	0.00
		$^4S_{3/2}$	0.00		520.026.	$^2D^0_{5/2}$	19224.464
	113.543	$^4P_{5/2}$	88107.260			$^4S_{3/2}$	0.00
		$^4S_{3/2}$	0.00	821.6	818.487	$^4P^0_{5/2}$	95532.150
116.8	116.745	$^2F_{7/2}$	104881.350			$^4P_{3/2}$	83317.830
		$^2D^0_{5/2}$	19224.464		818.802	$^4P^0_{3/2}$	95493.690
	116.842	$^2F_{5/2}$	104810.360			$^4P_{1/2}$	83284.070
		$^2D^0_{5/2}$	19224.464		820.036	$^4P^0_{1/2}$	95475.310
						$^4P_{1/2}$	83284.070

(continued)

Table 9.28 (continued)

Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})		Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})	
	821.072	$^4P^0_{3/2}$	95493.690	64.5	64.463	$^3S^0_1$	155126.73
		$^4P_{3/2}$	83317.830			$^3P_0$	0.00
	822.314	$^4P^0_{1/2}$	95475.310		64.484	$^3S^0_1$	155126.73
		$^4P_{3/2}$	83317.830			$^3P_1$	48.67
	821.634	$^4P^0_{5/2}$	95532.150		64.518	$^3S^0_1$	155126.73
		$^4P_{5/2}$	83364.620			$^3P_2$	130.80
821.6	824.239	$^4P^0_{3/2}$	95493.690	66.0	66.029	$^1P^0_1$	166765.66
		$^4P_{5/2}$	83364.620			$^1D_2$	15316.17
868.0	868.028	$^4D^0_{7/2}$	94881.820	67.1	67.102	$^3P^0_2$	149076.52
		$^4P_{5/2}$	83364.620			$^3P_1$	48.67
	868.340	$^4D^0_{5/2}$	94830.890		67.139	$^3P^0_2$	149076.52
		$^4P_{3/2}$	83317.830			$^3P_2$	130.80
	868.615	$^4D^0_{3/2}$	94793.490		67.141	$^3P^0_1$	148940.17
		$^4P_{1/2}$	83284.070			$^3P_0$	0.00
	870.325	$^4D^0_{1/2}$	94770.880		67.163	$^3P^0_1$	148940.17
		$^4P_{1/2}$	83284.070			$^3P_1$	48.67
	871.170	$^4D^0_{3/2}$	94793.490		67.177	$^3P^0_0$	148908.59
		$^4P_{3/2}$	83317.830			$^3P_1$	48.67
	871.883	$^4D^0_{5/2}$	94830.890		67.200	$^3P^0_1$	148940.17
		$^4P_{5/2}$	83364.620			$^3P_2$	130.80
	872.889	$^4D^0_{1/2}$	94770.880	74.6	74.584	$^1P^0_1$	166765.66
		$^4P_{3/2}$	83317.830			$^1S^0_0$	32688.64
	874.736	$^4D^0_{3/2}$	94793.490	74.7	74.698	$^1P^0_1$	149187.80
		$^4P_{3/2}$	83317.830			$^1D_2$	15316.17
1040.0	1039.77	$^2P^0_{3/2}$	28839.306	91.6	91.561	$^3P^0_1$	109216.44
		$^2D^0_{5/2}$	19224.464			$^3P_0$	0.00
	1040.73	$^2P^0_{3/2}$	28839.306	91.6	91.596	$^3P^0_0$	109223.34
		$^2D^0_{3/2}$	19233.177			$^3P_1$	48.67
	1040.76	$^2P^0_{1/2}$	28838.920		91.602	$^3P^0_2$	109216.93
		$^2D^0_{3/2}$	19233.177			$^3P_1$	48.67
Singly ionized nitrogen (NII)					91.602	$^3P^0_1$	109216.44
52.9	52,935	$^3P^0_1$	188909.17			$^3P_1$	48.67
		$^3P_0$	0.00		91.671	$^3P^0_2$	109216.93
	52,941	$^3P^0_0$	188937.24			$^3P_2$	130.80
		$^3P_1$	48.67		91.671	$^3P^0_1$	109216.44
52.9	52,949	$^3P^0_1$	188909.17			$^3P_2$	130.80
		$^3P_1$	48.67	108.5	108.399	$^3D_1$	92251.46
	52.964	$^3P^0_2$	188857.37			$^3P_0$	0.00
		$^3P_1$	48.67		108.457	$^3D_1$	92251.46
52.9	52.972	$^3P^0_1$	188909.17			$^3P_1$	48.67
		$^3P_2$	130.80		108.458	$^3D_2$	92249.91
	52.987	$^3P^0_2$	188857.37			$^3P_1$	48.67
		$^3P_2$	130.80		108.553	$^3D_1$	92251.46
						$^3P_2$	130.80

(continued)

Table 9.28 (continued)

Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})		Nominal λ (nm)	Fine structure	Term energies involved (cm^{-1})	
	108.555	$^3D_2$	92249.91		504.072	$^3F^0_2$	186511.58
		$^3P_2$	130.80			$^3D_3$	166678.64
	108.571	$^3D_3$	92236.46	504.5	500.270	$^3S_1$	168892.21
		$^3P_2$	130.80			$^3P^0_0$	148908.59
306.0	306.284	$^1S^0_0$	32688.64		501.062	$^3S_1$	168892.21
		$^3P_1$	48.67			$^3P^0_1$	148940.17
463.0	460.148	$^3P_2$	170666.23	504.5	504.510	$^3S_1$	168892.21
		$^3P^0_1$	148940.17			$^3P^0_2$	149076.52
	460.716	$^3P_1$	170607.89	567.9	566.663	$^3D_2$	166582.45
		$^3P^0_0$	148908.59			$^3P^0_1$	148940.17
	461.387	$^3P_1$	170607.89		567.602	$^3D_1$	166521.69
		$^3P^0_1$	148940.17			$^3P^0_0$	148908.59
463.0	462.139	$^3P_0$	170572.61		567.956	$^3D_3$	166678.64
		$^3P^0_1$	148940.17			$^3P^0_2$	149076.52
	463.054	$^3P_2$	170666.23		568.621	$^3D_1$	166521.69
		$^3P^0_2$	149076.52			$^3P^0_1$	148940.17
	464.308	$^3P_1$	170607.89		571.077	$^3D_2$	166582.45
		$^3P^0_2$	149076.52			$^3P^0_2$	149076.52
500.1	500.113	$^3F^0_2$	186511.58		573.064	$^3D_1$	166521.69
		$^1D_1$	166521.69			$^3P^0_2$	149076.52
	500.148	$^3F^0_3$	186570.98	575.5	575.464	$^1S_0$	32688.64
		$^3D_2$	166582.45			$^1D_2$	15316.17
	500.515	$^3F^0_4$	186652.49	658.3	654.801	$^1D_2$	15316.17
		$^3D_3$	166678.64			$^3P_1$	48.67
	501.638	$^3F^0_2$	186511.58		658.344	$^1D_2$	15316.17
		$^3D_2$	166582.45			$^3P_2$	130.80
	502.567	$^3F^0_3$	186570.98				
		$^3D_3$	166678.64				

[a]Observed transitions according to Rees (1989), energy levels from Sansonetti and Martin (2005), fine structure wavelengths are calculated, with values greater than 200 nm corrected from vacuum to air: $\lambda_{air} = \lambda_{vac}/n$, where n is the (wavelength-dependent) refractive index of air. Additional transitions given by Rees (1989) are for OI: 81.1, 87.8, 99.9, 115.2, 121.8, 436.8, 496.8, 799.0; OII 44.2; NI: 95.3, 110, 106.9, 116.4, 117.7, 118.9, 493.5; NII: 62.9, 63.5, 214.3, 500.6 (nominal wavelengths (nm))

Table 9.29 Term energies, life times, vibrational constants, and band systems of O_2, N_2 and NO observed in airglow and aurora[a]

	Term	T_e (cm^{-1})	Life time	ω_e	$\omega_e x_e$	Transition
O_2	$B\,^3\Sigma_g^-$	49793.3		709.31	10.65	Schumann-Runge ($B\,^3\Sigma_g^- \leftarrow X\,^3\Sigma_g^-$)
	$A\,^3\Sigma_u^+$	35397.8	0.18 s	799.7	12.16	Herzberg I ($A\,^3\Sigma_g^+ \rightarrow X\,^3\Sigma_g^-$)
	$A'\,^3\Delta_{u3}$	34605.8	2 s	817.6	12.76	Chamberlain ($A'\,^3\Delta_u \rightarrow a\,^1\Delta_g$)
	$A'\,^3\Delta_{u2}$	34756.2	1.5 s			Herzberg III ($A'\,^3\Delta_u \rightarrow X\,^3\Sigma_g^-$)
	$c\,^1\Sigma_u^-$	33057.3	3 s	794.2	12.73	Herzberg II ($c\,^1\Sigma_u^- \rightarrow X\,^3\Sigma_g^-$)
	$b\,^1\Sigma_g^+$	13195.1	12 s	1432.77	14.0	Atmospheric ($b\,^1\Sigma_g^+ \rightarrow X\,^3\Sigma_g^-$)
	$a\,^1\Delta_g$	7918.1	4 ks	1510.23	13.37	IR Atmospheric ($a\,^1\Delta_g \rightarrow X\,^3\Sigma_g^-$)
	$X\,^3\Sigma_g^-$	0.0		1580.19	11.98	
O_2^+	$b\,^4\Sigma_g^-$	49552	1.15 µs	1196.77	17.09	1st negative ($b\,^4\Sigma_g^- \rightarrow a\,^4\Pi_u$)
	$a\,^4\Pi_u$	32964		1035.69	10.39	
	$X\,^2\Pi_g$	0.0		1904.77	16.26	
N_2	$C\,^3\Pi_u$	89136.9	40 ns	2047.18	28.445	2nd positive ($C\,^3\Pi_u \rightarrow B\,^3\Pi_u$)
	$a\,^1\Pi_g$	69283.1	100 µs	1694.20	13.949	LBH ($a\,^1\Pi_g \rightarrow X\,^1\Sigma_g^+$)
	$B\,^3\Pi_g$	59619.3	5 µs	1733.39	14.122	1st positive ($B\,^3\Pi_u \rightarrow A\,^3\Sigma_g^+$)
	$A\,^3\Sigma_u^+$	50203.6	2.5 s	1460.64	13.87	Vegard-Kaplan ($A\,^3\Sigma_g^+ \rightarrow X\,^1\Sigma_g^+$)
	$X\,^1\Sigma_g^+$	0.0		2358.57	14.324	
N_2^+	$B\,^2\Sigma_u^+$	25461.4	60 ns	2419.84	23.19	1st negative ($B\,^2\Sigma_g^+ \rightarrow X\,^2\Sigma_g^+$)
	$A\,^2\Pi_u$	9166.9	14 µs	1903.70	15.02	Meinel bands ($A\,^2\Pi_u \rightarrow X\,^2\Sigma_g^+$)
	$X\,^2\Sigma_g^+$	0.0				
NO	$C\,^2\Pi_r$	52126.0	20 ns	2395	15	δ-bands ($C\,^2\Pi_r \rightarrow X\,^2\Pi_r$)
	$B\,^2\Pi_r$	45913.6	1.8 µs	1037.2	7.70	β-bands ($B\,^2\Pi_r \rightarrow X\,^2\Pi_r$)
	$A\,^2\Sigma^+$	43965.7	210 ns	2374.31	16.106	γ-bands ($A\,^2\Sigma^+ \rightarrow X\,^2\Pi_r$)
	$X\,^2\Pi_r$	0.0		1904.20	14.075	

[a]Energy units of term electronic energy T_e and vibrational constants ω_e, $\omega_e x_e$ are (cm^{-1}). Data sources: Huber and Herzberg (1979), Slanger and Huestis (1983), Bates (1988); lifetimes are approximate; they depend on the vibrational level and the occurrence of predissociation. Vibrational energy levels can be calculated from the expression $G(\upsilon) = T_e + \omega_e(\upsilon + ½) - \omega_e x_e(\upsilon + ½)^2$

Table 9.30 Band origins of the O_2 Herzberg I ($A\,^3\Sigma_u^+ \rightarrow X\,^3\Sigma_g^-$) system[a]

$\upsilon' \backslash \upsilon'' =$	0	1	2	3	4	5	6	7	8	9	10	11	12
0	285.6	298.9	313.2	328.7	345.7	364.1	**384.3**	**406.5**	**431.1**	458.3	488.8	523.1	562.0
1	279.4	292.1	305.8	320.6	336.7	**354.1**	**373.2**	**394.1**	417.2	442.6	471.0	502.8	538.6
2	273.7	285.9	299.0	313.1	328.4	**345.0**	**363.1**	**382.9**	404.6	428.5	455.1	484.6	517.8
3	268.5	280.2	292.8	**306.3**	**320.9**	**336.8**	**354.0**	372.7	393.3	415.8	440.8	468.5	499.4
4	263.7	**275.0**	**287.1**	**300.1**	**314.1**	**329.3**	**345.7**	363.6	383.1	404.5	428.0	454.1	483.1
5	**259.4**	**270.3**	**281.9**	**294.5**	**308.0**	**322.5**	338.3	355.4	374.0	394.3	416.7	441.3	468.7
6	**255.4**	**266.0**	**277.3**	**289.4**	**302.4**	**316.5**	**331.6**	348.0	365.9	385.3	406.6	430.1	456.0
7	**251.9**	**262.2**	**273.2**	**284.9**	**297.5**	**311.1**	**325.7**	341.5	358.7	377.3	397.8	420.2	444.9
8	248.9	**258.9**	**269.6**	**281.1**	293.3	306.5	320.6	335.9	352.4	370.3	389.8	422.2	434.3
9	246.3	**256.2**	**266.6**	277.8	289.8	302.6	316.4	331.3	347.3	364.7	383.6	404.2	426.7
10	244.3	254.0	264.3	275.2	287.0	299.6	313.1	327.6	343.3	360.3	378.7	398.7	420.6

[a]Observed transitions are accentuated, wavelengths (nm) in air; Data sources: Degen (1977), Rees (1989)

Table 9.31 Band origins in the O_2 Herzberg II ($c\ ^1\Sigma_u^- \rightarrow X\ ^3\Sigma_g^-$) system[a]

$v'\backslash v''$	0	1	2	3	4	5	6
0	306.1	321.4	338.0	356.2	376.1	398.1	422.3
1	299.0	313.6	329.5	346.7	365.6	386.3	409.1
2	292.5	306.5	321.6	338.0	355.9	375.5	397.0
3	286.6	300.0	314.4	330.1	347.2	**365.8**	386.1
4	281.1	284.0	307.8	**322.9**	**339.1**	**356.9**	376.2
5	276.1	288.5	301.8	**316.2**	**331.8**	**348.8**	367.3
6	271.5	283.4	296.3	**310.2**	325.2	341.5	**359.2**

[a]Observed transitions are accentuated, wavelengths (nm) in air; Data sources: Gadsden (1996), Slanger and Huestis (1981)

Table 9.32 Band origins in the O_2 Chamberlain ($A'\ ^3\Delta_u$ – $a\ ^1\Delta_g$) system[a]

$v'\backslash v''$	0	1	2	3	4	5	6	7	8
0	379.5	402.1	427.2	455.0	486.0	520.9	560.3	605.2	656.7
1	368.4	389.8	413.2	439.3	**468.0**	500.3	536.5	577.5	624.3
2	358.4	378.5	400.6	**424.9**	**451.9**	**481.9**	515.4	553.1	595.9
3	349.2	**368.3**	**389.2**	**412.1**	**437.4**	**465.4**	496.6	531.6	570.9
4	340.9	**359.0**	**378.9**	**400.6**	**424.4**	450.8	480.0	512.6	549.1
5	333.4	**350.8**	**369.7**	**390.3**	**412.9**	437.8	465.3	495.9	429.9
6	326.8	**343.4**	**361.5**	**381.2**	402.8	426.4	452.5	481.9	513.3

[a]Observed transitions are accentuated, wavelengths (nm) in air; Data source: Slanger (1979)

Table 9.33 Origins of the OH rotation-vibration bands[a]

$v'\backslash v''$	0	1	2	3	4	5	6	7	8
1	2801.3								
2	1434.0	2937.8							
3	**979.0**	1505.0	3085.9						
4	**752.3**	1028.5	1582.6	3248.6					
5	**617.0**	**791.2**	1082.8	1668.2	3429.0				
6	**527.4**	**649.8**	**834.1**	1143.2	1763.8	3632.1			
7	464.1	**556.2**	**686.1**	**882.2**	1211.2	1872.5	3865.3		
8	417.3	490.3	**588.5**	**727.3**	**937.0**	1289.3	1998.8	4139.3	
9	381.7	441.9	**520.1**	**625.5**	**774.7**	**1000.8**	1381.4	2189.6	4472.0

[a]Observed transitions are accentuated, wavelengths (nm) in air; Data sources: Gadsden (1996), Broadfoot and Kendall (1968)

Table 9.34 Band origins in the O_2 infrared atmospheric systems[a]

	Atmospheric bands ($b\,^1\Sigma_g^+ - X\,^3\Sigma_g^-$)					Infrared atmospheric bands ($a\,^1\Delta_g - X\,^3\Sigma_g^-$)			
$\upsilon'\backslash\upsilon''$	0	1	2	3	$\upsilon'\backslash\upsilon''$	0	1	2	3
0	**761.9**	**864.5**	996.6	1173.1	0	**1270.4**	**1583.6**	2091.4	3056.8
1	688.2	770.8	874.2	1007.1	1	1071.8	1286.5	1602.7	2114.4
2	628.7	696.7	780.2	884.4	2	929.2	1086.3	1303.5	1622.9
3	579.5	637.0	705.9	790.2	3	821.8	942.4	1101.5	1321.3

[a]Observed transitions are accentuated, wavelengths (nm) in air; Data sources: Gadsden (1996), Rees (1989)

Table 9.35 Neutral iron chemistry in the mesosphere: Reactions and rate coefficients[a]

Reaction	A	B	α
$Fe + O_3 \rightarrow FeO + O_2$	3.44 (−10)	146	0
$Fe + O_2 + M \rightarrow FeO_2 + M$	8.7 (−30)	2,038	0
$FeO + O \rightarrow Fe + O_2$	4.6 (−10)	350	0
$FeO + O_3 \rightarrow FeO_2 + O_2$	2.94 (−10)	174	0
$FeO + O_2 + M \rightarrow FeO_3 + M$	3.86 (−30)	0	0.5
$FeO + H_2O + M \rightarrow Fe(OH)_2 + M$	8.23 (−29)	0	−1.16
$FeO + CO_2 + M \rightarrow FeCO_3 + M$	3.09 (−31)	0	−1.19
$FeO_2 + O \rightarrow FeO + O_2$	1.4 (−10)	580	0
$FeO_3 + O \rightarrow FeO_2 + O_2$	2.3 (−10)	2,310	0
$FeO_2 + O_3 \rightarrow FeO_3 + O_2$	4.4 (−10)	170	0
$FeO_3 + H \rightarrow FeOH + O_2$	3.0 (−10)	796	0
$FeO_3 + H_2O \rightarrow Fe(OH)_2 + O_2$	5.0 (−12)		
$Fe(OH)_2 + H \rightarrow FeOH + H_2O$	4.4 (−10)	302	0
$FeOH + H \rightarrow FeO + H_2$	2.5 (−10)	850	0
$FeOH + H \rightarrow Fe + H_2O$	2.0 (−12)	600	0

[a]Powers of ten in parentheses; $k = A\ (T/300)^{\alpha}\ \exp(-B/T)$ in units of (cm^3 $molecule^{-1}$ s^{-1}) for bimolecular reactions and (cm^6 $molecule^{-2}$ s^{-1}) for termolecular reactions, respectively. Source of data: Plane et al. (2003), Plane (2003)

Table 9.36 Sodium chemistry in the mesosphere: Reactions and rate coefficients[a]

Reaction	A	B	α	Notes[b]
$Na + O_3 \rightarrow NaO + O_2$	1.1 (−9)	116	0	1
$NaO + O \rightarrow Na + O_2$	2.2 (−10) (overall)	0	0.5	2
$\rightarrow Na^* + O_2$	~2.7 (−11)			2
$NaO + O_3 \rightarrow NaO_2 + O_2$	1.1 (−9)	568	0	
$NaO + O_3 \rightarrow Na + 2\,O_2$	3.2 (−10)	550	0	
$Na + O_2 + M \rightarrow NaO_2 + M$	5.0 (−30)	0	−1.22	
$NaO_2 + O \rightarrow NaO + O_2$	5.0 (−10)	940	0	
$NaO + O_2 + M \rightarrow NaO_3 + M$	5.3 (−30)	0	−1	
$NaO_3 + O \rightarrow Na + 2\,O_2$	2.5 (−10)	0	0.5	3
$NaO + H_2O \rightarrow NaOH + OH$	4.4 (−10)	507	0	

(continued)

Table 9.36 (continued)

Reaction	A	B	α	Notes[b]
$NaO + H_2 \rightarrow NaOH + H$	1.1 (−9)	1,100	0	
$NaO + H_2 \rightarrow Na + H_2O$	1.1 (−9)	1,400	0	
$NaO + H \rightarrow Na + OH$	1.0 (−10)	668	0	
$NaO_2 + H \rightarrow Na + HO_2$	1.0 (−9)	1,000	0	
$NaO + CO_2 + M \rightarrow NaCO_3 + M$	1.3 (−27)	0	−1	
$NaCO_3 + O \rightarrow NaO_2 + CO_2$	5.0 (−10)	1,200	0	
$NaCO_3 + H \rightarrow NaOH + CO_2$	1.0 (−9)	1,400	0	
$NaOH + H \rightarrow Na + H_2O$	4.0 (−11)	550	0	
$NaOH + CO_2 + M \rightarrow NaHCO_3 + M$	1.9 (−28)	0	−1	
$NaHCO_3 + H \rightarrow Na + H_2O + CO_2$	1.0 (−12)	590	0	3
Photodissociation Reactions				
$Na + h\nu \rightarrow Na^+ + e^-$	2.0 (−5) (s^{-1})			
$NaO_2 + h\nu \rightarrow Na + O_2$	4.0 (−3) (s^{-1})			
$NaOH + h\nu \rightarrow Na + OH$	1.0 (−3) (s^{-1})			3
$NaO_3 + h\nu \rightarrow NaO + O_2$	1.0 (−4) (s^{-1})			3

[a]Powers of ten in parentheses; $k = A\,(T/T_{ref})^{\alpha} \exp(-B/T)$ with reference temperature $T_{ref} = 200$ K; units: (cm^3 $molecule^{-1}$ s^{-1}) or (cm^6 $molecule^{-2}$ s^{-1}) for bimolecular and termolecular reactions, respectively. Source of data: Plane et al. (1999), Plane (2003)

[b]Notes: (1) NaO is produced almost entirely in the long-lived, low-lying ($A^2\ \Sigma^+$) excited electronic state, which is not efficiently quenched; (2) Na* designates the Na (^2P_j) excited state, Na the Na ($^2S_{½}$) ground state; (3) These values are estimates

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