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PAPER 4

RÉSUMÉ OF THE PROBLEM OF CROSS-SECTIONS OF SOLAR RADIATION

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1. ABSORPTION OF X-RAYS BETWEEN 1 AND 10Å

The absorption of X-rays is related more to the concentration than to the nature of the elements when their atomic masses are not too different. For such a reason, the absorption by the principal constituents must be considered in the homosphere. Between 0·01 Å and 10 Å the cross-sections vary from about 3×10^{-24} cm^2 to 10^{-19} cm^2. It can be seen that the absorption peak for wavelengths between 0·01 and 7 Å occurs in the stratosphere from 27·5 to 50 km. The mesospheric absorption corresponds to a spectral range between 0·7 Å and 7 Å.

The effect of the absorption of X-rays leads to several effects and it is necessary to analyse the results for the atmospheric constituents. Radiations of short wavelengths subject to absorption initially cause photoionization. The ionization thresholds for oxygen and nitrogen being about 23 Å and 31 Å, respectively, the photoelectric electrons will produce other ionization effects when their energies are sufficiently high. Furthermore, for radiations of wavelengths shorter than 0·5 Å, Compton diffusion must be added to the photoelectric effect and the decrease of the total cross-section with wavelength becomes less important. Nevertheless, for any absorption process, the final result is the ionization of oxygen and nitrogen. In fact, the number of electrons produced corresponds to the use of 35 eV per ion pair. It is therefore possible to determine the number of electrons produced per solar photon. The approximate values are for $\lambda > 1$ Å:

	6 Å	4 Å	2 Å
Efficiency (electrons)	45	75	165

As far as the shortest wavelengths are concerned, the efficiency is very high:

	0·62 Å (20 keV)	0·31 Å (40 keV)	0·124 (100 keV)
Efficiency (electrons)	570	1140	2860

One may conclude that ionization due to X-rays of wavelengths shorter than 10 Å occurs in the D region of the ionosphere.

2. ABSORPTION OF X-RAYS BETWEEN 10Å AND 100Å

The K limits of carbon, nitrogen and oxygen, belong to the spectral range between 10 Å and 100 Å. The spectral distribution of the absorption by these three elements and the atmospheric absorption corresponds to cross-sections between 10^{-19} and 10^{-18} cm^2. The unit optical depth for the whole spectral range is concentrated in the layer about 20 km thick centred near 110 km. One can therefore deduce a close association with the E layer of the ionosphere. It must be pointed out that two spectral ranges must be considered; these relate to the absorption for wavelengths greater or less than 31 Å. In fact, ionization for $\lambda > 31$ Å occurs in the L continuum and for $\lambda < 23$ Å corresponds to the K continuum. The first spectral range will be more efficient in atmospheric ionization since solar energy at $\lambda > 31$ Å is greater than at $\lambda < 31$ Å. Nevertheless, other possibilities such as ionization by ultraviolet radiations and various recombination effects must be considered before studying the ionization equilibrium of the E layer.

3. ABSORPTION OF ULTRAVIOLET RADIATION SHORTER THAN 1000 Å

The study of ultraviolet absorption is more complicated than that of X-rays since it must be analysed for each constituent. Atoms and molecules have very different cross sections even in the same spectral range. But, it is necessary to try an analysis of the absorption behaviour in order to find some conclusions of a general nature. When one compares ionization potentials of atoms and molecules which are greater than that of molecular oxygen (see Table 1), one can see that O_2 absorption limits the penetration of solar radiation capable of ionizing polyatomic molecules whose ionization potential is between 1010 Å and 940 Å. Molecules such as CH_4, O_3, H_2O, NO_2 and N_2O can be neglected in the atmospheric ionization since photodissociation processes will play the leading role and no radiation will be available to ionize these molecules in lower regions where their concentration would have been sufficient.

In the same way, CO and CO_2 and inert gases such as A, Ne, He will not participate sufficiently in the atmospheric ionization since atomic oxygen is

Table 1. Ionization Thresholds of Atoms and Molecules for $\lambda \leqslant 1026$ Å

Constituent	λ	*Constituent*	λ
O_2	1026	O	910
NO_2	1008	CO_2	899
H_2O	985	CO	885
O_3	969	N	852
N_2O	961	N_2	796
CH_4	954	A	787
OH	940	Ne	575
H	911	He	504

photionized at $\lambda \leqslant 910$ Å and molecular nitrogen at $\lambda \leqslant 796$ Å. These two constituents together with molecular oxygen will limit the photoionization of all other constituents in the thermosphere.

Molecular oxygen has several ionization potentials corresponding to electronic states of the ionized molecules:

	$^2\Pi$	$^4\Pi_u$	$^2\Pi_u$	$^4\Sigma_g^-$
λ	1026·5	770	737	682
eV	12·08	16·10	16·85	18·17

The ionization cross-section is always less than 4×10^{-18} cm^2 in the continuum corresponding to the absorption spectral range of the first ionization potential (1026 Å $\leqslant \lambda \leqslant$ 910 Å). One can see, however, that the ionization cross-section does not follow the continuum distribution but depends on the structure of absorption bands which are, in fact, pre-ionization bands in several cases. As a result, the ionization cross-section has a very complicated structure. The example of the Lyman-series of hydrogen shows how much the ionization efficiency is related to the detailed structure of the absorption spectrum. It is very difficult to obtain exact values of ionization coefficients when the spectrum of oxygen with superposed absorption bands is associated with the solar spectrum which also has a complicated structure in that spectral range. Furthermore, when the absorption occurs in a particular band, it is necessary to know the exact fraction associated with the ionization cross-section. Lyman-β at 1025·7 Å is a typical example; its ionization cross-section is equal to 9×10^{-19} cm^2 and its total absorption cross-section is $1{\cdot}55 \times 10^{-18}$ cm^2. Such values of the absorption of Lyman-β show that an absorption peak must occur inside of the E layer, where X-rays of $\lambda > 10$ Å are also absorbed.

Experimental data, based on the absorption of monochromatic radiations inside of molecular bands, may be different since the rotational structure is related to temperature. It must therefore be stressed that when experimental data are used for aeronomic purposes special care must be taken. When measurements are related to a continuum, results obtained with sufficient resolution can be applied to the atmosphere; but, when bands are involved, results should be considered as only indications leading to semi-quantitative values. This remark is of special importance in the study of the thermosphere where temperatures greater than 1000°K exist. Rotational structure and even vibrational distribution may modify experimental data obtained at lower temperatures.

The beginning of the ionization continuum of atomic oxygen is subject to the simultaneous absorption of another constituent in the atmosphere and consequently the complexity of the real absorption. In the same way, absorption bands of molecular nitrogen should be introduced in that spectral region. In fact, the whole spectrum from 1030 Å to 850 Å includes nitrogen bands with complicated structure. Although the position of these bands in the spectrum is known, it is not yet possible to give correct limits to the absorption cross-sections. On the other hand, experimental determinations made at too low a dispersion cannot be used unless the rotational distribution is known. In fact, variations of several orders of magnitude must be expected in very short spectral intervals. In other words, two solar radiations in the same spectral range may correspond to a region in the atmosphere where the absorption is strong and to an atmospheric window with deep atmospheric penetration, respectively. As an example, Lyman-γ at 972·5 Å and Lyman-δ at 949·7 Å have absorption cross-sections which differ by a factor of 10 in molecular oxygen. The exact values, however, depend on the temperature of the absorbing gas.

The cross-sections of atomic oxygen are theoretical values; extrapolation from 100 Å may be made for the range of shortest wavelengths. Discontinuities correspond to various thresholds:

O^+	$2p^3\ {}^4S^\circ_{3/2}$	${}^2D^\circ_{5/2,\ 3/2}$	${}^2P^\circ_{3/2,\ 1/2}$	$2p^4\ {}^4P$	${}^2P$
λ eV	910·4 13·6	731·8 16·9	665·3 18·6	436 28·5	310 40·0

The essential behaviour of the absorption spectrum is that the cross-section varies by a factor of 5 in the spectral range between 910 Å and 150 Å and by about a factor of 2 between 730 Å and 250 Å. An average value of

$$(1 \pm 0{\cdot}25) \times 10^{-17}\,\text{cm}^2$$

can be used between 730 Å and 250 Å. A value of the order of 3×10^{-18} cm^2 should be used between 910 Å and 732 Å and also in a part of the spectrum between 200 Å and 150 Å.

The ionization cross-section of molecular oxygen has some tendency to be twice that of atomic oxygen. But, a detailed analysis shows that the structure is more complicated, due to the presence of important bands. In fact, there are differences between various experimental data, and absorption cross-sections. For example, the absorption cross-section at 797 Å is $3{\cdot}5 \times 10^{-17}$ cm^2 whilst that of ionization is only $0{\cdot}8 \times 10^{-17}$ cm^2.

Due to the difficulty of obtaining sufficiently precise values, it should be remembered that an average value, of the order of $(2{\cdot}5 \pm 0{\cdot}5) \times 10^{-17}$ cm^2, should be used as a first approximation for the 750–400 Å range; 2×10^{-17} cm^2 can be considered as a minimum value. In the spectral range of wavelengths shorter than 400 Å, the ionization cross-section is nevertheless greater than 10^{-17} cm^2.

Molecular nitrogen, for which several experimental determinations have been made, has an absorption spectrum which is, however, not well known. Its analysis is less precise than that of molecular oxygen. If it is clear, however, that the ionization cross-section of the continuum is greater than 10^{-17} cm^2 from the first ionization potential at $\lambda = 795{\cdot}8$ Å to 500 Å, it is difficult to choose from among the possible values between 500 Å and 200 Å. Since the experimental data is not precise enough for the whole spectrum, one must adopt an average value between 795 Å and 350 Å corresponding to $1{\cdot}5 \pm 0{\cdot}5) \times 10^{-17}$ cm^2. As far as values at specified wavelengths are concerned, it is not possible to adopt consistent cross-sections. There is perhaps an exception for $\lambda = 584$ Å corresponding to the resonance line of neutral helium for which the absorption cross-section by molecular nitrogen would be $(1{\cdot}8 \pm 0{\cdot}2) \times 10^{-17}$ cm^2.

In conclusion, the absorption cross-section of the principal constituents of the thermosphere are not known with sufficient precision for a complete analysis of the ionization processes. Since data must be used for aeronomic problems, one must remember that the ultraviolet spectrum is characterized by absorption cross-sections of the order of 10^{-17} cm^2 whilst the X-ray spectrum between 100 and 10 Å leads to cross-sections from 10^{-19} cm^2 to 10^{-18} cm^2. Absorption of solar radiations in the ultraviolet and X-ray ranges will appear in different atmospheric regions. If X-rays are absorbed in the E layer, the ultraviolet absorption will be effective in the F region.

4. IONIZATION BY ULTRAVIOLET OF $\lambda > 1000$ Å

Some indications can be given of the possible ionization processes related to the spectral range of $\lambda > 1026{\cdot}5$ Å associated with the first ionization potential of molecular oxygen. A list of atoms and molecules which may be involved

Table 2. Ionization Thresholds of Atoms and Molecules for λ > 1026 Å

Atoms	λ	*Molecule*	λ
Na	2412	NO	1340
Al	2071	CH_3	1260
Ca	2028	NH_3	1221
Mg	1622	CH	1117
Si	1521		
C	1100		

is given in Table 2. Nothing is known about the cross-section of CH_3 and CH. Very precise measurements have been made for nitric oxide. At Lyman-α, the absorption cross-section is $2{\cdot}42 \times 10^{-18}$ cm^2 and the ionization cross-section equals $2{\cdot}02 \times 10^{-18}$ cm^2.

Sodium, calcium, magnesium, etc., cannot be neglected since their ionization thresholds occur at wavelengths for which solar radiation is important. Their ionization coefficients should be between 10^{-5} sec^{-1} and 10^{-6} sec^{-1}.

REFERENCES

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