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Origin of the Ionospheric *E* Layer

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The intensity of solar soft x-rays (50···230A) as computed by Elwert is found to be sufficient to cause the ionization of the ionospheric *E* layer. On the other hand, preionization of molecular oxygen by ultraviolet chromospheric radiation ($\lambda < 1020$A, Nicolet) could perhaps also be admitted, if it could be accepted that the dissociation of atmospheric oxygen occur in a high transition layer of considerable thickness (100–150 km). The first process is probably predominant.

1. INTRODUCTION

According to the usual theory the *E* layer is formed by ionization of molecular oxygen by ultraviolet radiation. In 1948 Bates and Hoyle[1] proposed a theory of formation by solar x-rays at about 40A. In a first note in 1951,[2] we pointed out some difficulties of the usual theory and mentioned the x-ray theory as one possible solution. Meanwhile Elwert[3] has calculated x-ray emission from the solar corona; he found that a softer radiation (50 to 200A) should be most important for the formation of the ionospheric *E* layer.

While x-rays would cause ionization of all atmospheric molecules, the commonly accepted process should be selective and concern only oxygen molecules. Nicolet[4] suggested the wavelength range 900 to 1000A as responsible for ionization of O_2 by an assumed preionization effect.

In this situation the two theories and the corresponding deductions must be compared. This has recently been done by Choudhury[5] who calculated the absorption cross sections required in the two theories, and in more detail by the present authors.[6] We feel that a *mutual* comparison of these results together with recent developments in this field should be of interest.

2. IONIZATION OF O_2 BY ULTRAVIOLET LIGHT

If O_2 is ionized in a specific process, the shape of the corresponding layer, i.e., its height and thickness, will depend on the distribution of O_2 molecules and on the cross section of the process itself. On the other hand, the resulting ionization depends essentially on the intensity of the ionizing radiation.

Distributions of Molecular Oxygen

Many authors, including Penndorf,[7] suppose that molecules recombine by a three-body collision process. This process depends in a sensitive manner on the molecular density. The resulting transition layer is sharp (about 10 km), and its height is lower than that obtained for the *E* layer by radio measurements (maximum at about 125 km). This is an important difficulty because there is only one parameter at our disposal (i.e., the cross section of ionization) to adjust to the well-known height and thickness of the ionized layer; we can prove that this is not possible when the transition is sharp and low.[6] In our former discussion,[2] we pointed out that perhaps another recombination process should be considered. Recombination by radiative two-body collision has already been considered by Majumdar[8] who found a very high transition layer. While Rakshit[9] with the same hypothesis obtained a low and very thin transition, recently Moses and Wu[10] arrived at a layer of more than 30-km thickness situated between 100 and 130 km (see Fig. 1).

We think that the discussion on O_2 dissociation is not yet final. Penndorf's calculation is heavily critized by Moses and Wu. But these authors consider only the contribution of oxygen to the energy balance which determines the temperature. It seems doubtful whether this is justified on account of the radiation absorbed by nitrogen.

The theoretical approaches made hitherto are based only on static considerations, neglecting completely dynamical influences. It is now well known that turbulent movements and ionospheric winds are rather important in the *E* layer. In that case the thickness of the transition layer, obtained by static calculations only, cannot be identified with the observed parameters of a real layer.[11] We can suppose that even the sharp theoretical transition layers calculated by Penndorf (Fig. 1) are extended by turbulence. Thus, without judging the different hypotheses, we think that the numerical results of Moses and Wu are approximately acceptable. Recent rocket observations at 1475A show that absorption begins at 140 km and reaches a maximum at 105 km.[12] As this wavelength is absorbed by O_2, this result must be interpreted in favor of a broad transition layer situated between 90 and 150 km.

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[1] D. R. Bates and F. Hoyle, Terr. Mag. **53**, 51 (1948).
[2] E. Argence and K. Rawer, Compt. rend. **233**, 1208 (1951).
[3] G. Elwert, Z. Naturforsch. **7a**, 202 (1952).
[4] M. Nicolet, Mem. Roy. Met. Inst. Belgium **19**, 124 (1945).
[5] D. C. Choudhury, Phys. Rev. **88**, 405 (1952).
[6] E. Argence and K. Rawer, Ann. géophys. **9**, 1 (1953).
[7] R. Penndorf, J. Geophys. Research **54**, 7 (1949).
[8] R. C. Majumdar, Indian J. Phys. **12**, 75 (1938).
[9] H. Rakshit, Indian J. Phys. **21**, 57 (1947).
[10] H. E. Moses and T. Y. Wu, Phys. Rev. **83**, 109 (1951).
[11] M. Nicolet (private communication).
[12] Friedman, Lichtman, and Bryan, Phys. Rev. **83**, 1025 (1951).

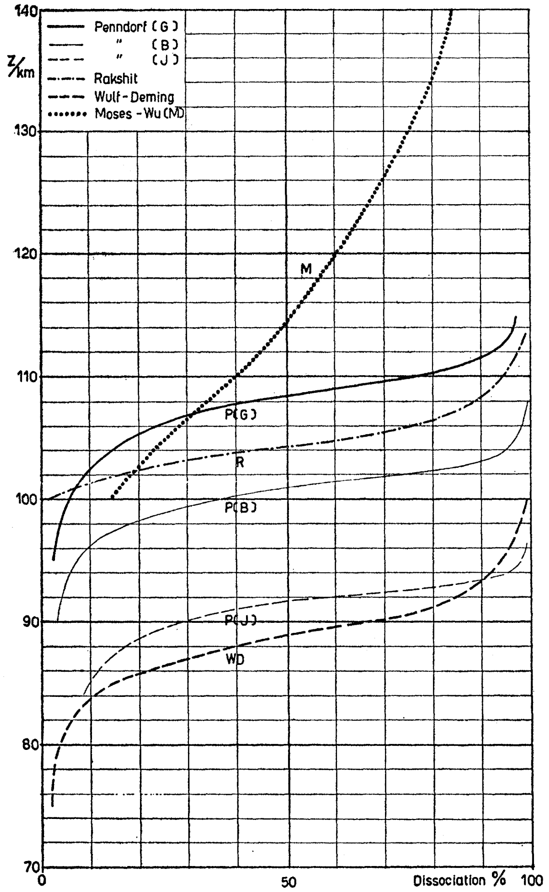

FIG. 1. Rate of dissociation of oxygen molecules in the high atmosphere.

Distribution of Ionization

We have calculated the ionization obtained in the case of a monochromatic radiation ionizing only O_2 molecules for some models of transition layers.[6] The distribution of the number density N' of O_2 is supposed to be

$$N'=N_0'(1-b_z')^{1/b'h_0}$$

above the lower transition limit. and a constant fraction of the total number density below it. The data of our four models A, B, C, D have been indicated in Fig. 2 together with Penndorf's theoretical density values and that of Moses and Wu. The corresponding ionization was calculated with different assumed absorption coefficients (*viz.*, cross sections) such that in each case the maximum of ionization was found at 125 km (this height is well known from ionospheric observations). Thus we obtain the ionization curves of Fig. 3. Curve C and D must be rejected because the calculated thickness is too small; curve B is most similar to the result of ionospheric observations on the E layer. The cross section effective for ionization should be 1.33×10^{-17} cm^2 in this case. Choudhury used a simple exponential variation of N' as an approximation to the values of Moses and Wu. He found a cross section of 0.66–0.88 $\times 10^{-17}$ cm^2; the maximum of ionization was assumed to be at 120 km. Taking account of the difference in altitude, the two results agree very well.

The corresponding model B for the transition layer (Fig. 2) is rather broad and high. In any case the transition should be found at high altitudes, if the usual theory of specific ionization could be acceptable at all.

Solar Radiation Causing Ionization

The intensity of solar radiation producing the E layer can be obtained from the observed electron density and the cross section calculated above; it should be 9.3×10^7 quanta cm^{-2} sec^{-1}. In the range of preionization, 900 to 1020A, the intensity in the solar spectrum at the top of the atmosphere is estimated to be several times this number.[13] Unfortunately, rocket measurements have not yet been made in this special wavelength range. Now Elwert[14] doubts whether this radiation could arrive at the altitude of 130 km without heavy losses by N_2 absorption. Recently published results on N_2 absorption[15] indicate a high absorption

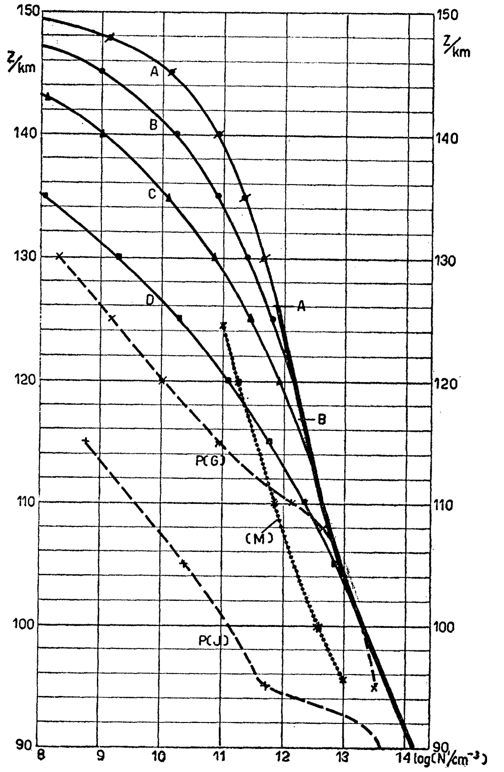

FIG. 2. Particle density of molecular oxygen (broken lines: results of Penndorf and Moses and Wu; full lines: our models A, B, C, D).

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[13] M. Nicolet, Ann. géophys. 8, 141 (1952).

[14] G. Elwert (private communication).

[15] Weissler, Lee, and Mohr, J. Opt. Soc. Am. 42, 84 (1952).

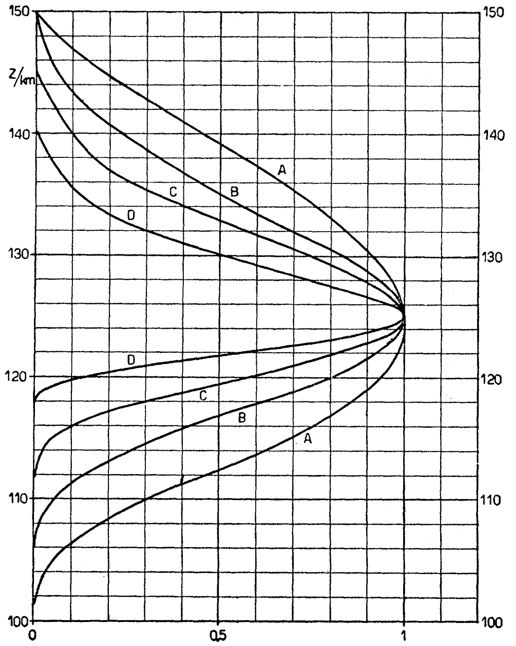

FIG. 3. Calculated electron density for our four models (the recombination coefficient has been assumed to be constant; the maximum electron density is the unit on the abscissa).

below 980A; the absorption is $\exp(-500z/\text{cm})$ for standard conditions. This radiation cannot reach the height of the *E* region. Above 980A there seems to exist a "window"; the absorption coefficient has a minimum at 1026A with 60 instead of 500 cm^{-1}. With this value we find an attenuation of $1/e$ at a pressure of 1.6×10^{-5}mm Hg for the case of absorption in the atmosphere.[16] This pressure exists at an altitude of about 130 km.[17,18] Only radiation from the "window" could thus reach the *E* region without a too heavy loss. It is questionable whether the amount of incoming radiation in the window is sufficient. As L_γ(972A) is outside the window, and as the quantum energy of L_β(1025A) is probably insufficient to produce preionization, Elwert's objection could be justified. Only if there were another important radiation between 980 and 1020A could the theory of preionization be maintained.

3. IONIZATION BY X-RAYS

In this case the ionization holds for all atmospheric molecules; an estimate of its effective section can be obtained with a simple model calculation. Instead of the exponential density variation used by Choudhury, we prefer a model with a linear variation of temperature.[19] The height of the maximum electron density, depends on the recombination law. We think there are arguments that it is nearer to a variation of α (the recombination coefficient) with the square root of number density[20] than to a constant value α. The condition for the maximum is[6]

$$\sigma\sec\chi N_mH_m/(1+bH_m)=\tfrac{1}{2}\quad\text{or}\quad 1,$$

for these two assumptions, where σ is the cross section, χ the zenith angle, N_m, H_m the number density and scale height at the height of the maximum, b the coefficient of the linear temperature gradient; $b\approx0.015$ km^{-1}. It follows for a maximum at 125 km that

$$\sigma\sec\chi=0.68\quad\text{or}\quad 1.35\times10^{-18}\ \text{cm}^2.$$

This is lower than Choudhury's estimate.[5] Consequently we think that a longer wavelength of radiation must be considered, namely 100$\cdots$200A (60$\cdots$120 ev, instead of 181).[21]

Elwert's calculation of solar x-ray emission[3] is based exclusively on astrophysical data. He only introduced

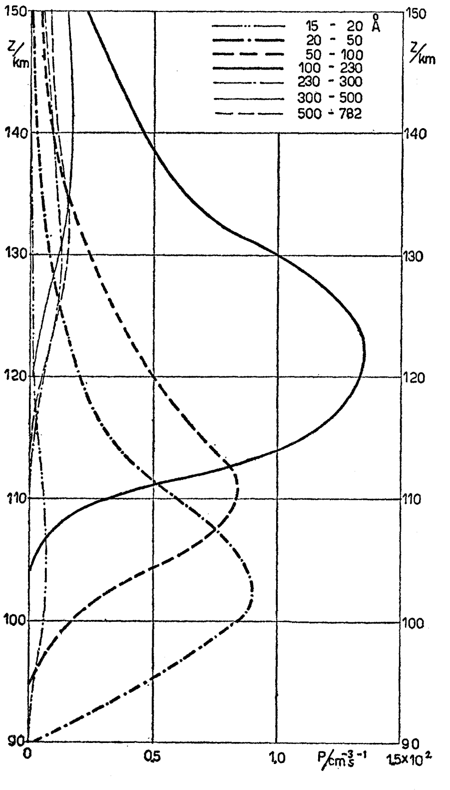

FIG. 4. Electron production for different wavelength ranges in the case of Elwert's corona model with 10^6 °K.

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[16] This N_2 absorption will not produce ionization because the quantum energy of 12$\cdots$13 ev is lower than the ionization potential of N_2.

[17] Havens, Koll, and La Gow, J. Geophys. Research **57**, 59 (1952).

[18] An eventual dissociation of N_2 does not seriously destroy this argument because it is certainly small at altitudes inferior to 150 km.

[19] J. A. Gledhill and M. E. Szendrei, Proc. Phys. Soc. (London) **B63**, 427 (1950); M. Nicolet and L. Bossy, Ann. géophys. **5**, 275 (1949).

[20] Argence, Mayot, and Rawer, Ann. géophys. **6**, 242 (1950).

[21] The rocket measurements of Friedman[12] concern only wavelengths below 10A; the maximum of absorption is obtained for 87 km. This radiation could thus be perhaps one cause of the ionization of the *D* layer, but not of the *E* layer.

the electron density of the solar corona, its temperature, and the cosmical relative abundance of elements. Taking account of ionization, recombination, and excitation he finds radiation by free-free, free-bound, and bound-bound transitions. The most important contribution comes from the latter; the most probable excitation process is by electron impact.

With Elwert's radiation values[3] obtained for a temperature of 10^6 °K and with the values of the absorption cross section given by Schneider[22] and Siedentopf,[23] we have calculated the absorption for different ranges of wavelength as a function of the height (Fig. 4.) The abcissas of the curves are proportional to the production rate of electrons. Summing up the different contributions, one obtains the total amount of production. From this, with assuming the coefficient of effective recombination to vary with the altitude,[24] we obtained the distribution of electron density (Fig. 5). We have assumed a high efficiency of ionization, only 15.8 ev for each ionization; perhaps this value should be as high as 30 ev,[25] but there is little information about very soft x-rays. From comparison with experimental curves of electron density (Fig. 5) it appears that the calculated maximum electron density is midway beween the experimental values corresponding to high and low solar activity. (If we had assumed a lower efficiency of ionization it would be about 30 percent lower). This is a very remarkable correspondence, because Elwert's numerical values come from astrophysical sources only; they do not contain any geophysical information. On the other hand, the theoretical curve of Fig. 5 gives a layer of larger thickness than the ionospheric records show. One sees from Fig. 4 that this is caused by the radiation of short wavelength, below 50A.

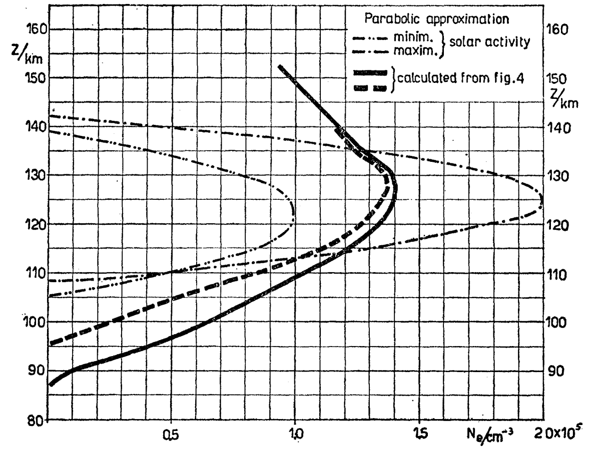

FIG. 5. Resulting electron density obtained from Fig. 4 (broken line, when the radiation ceases at 50A). Thin lines: parabolic models with parameters obtained from observations (only the lower half of these curves is physically significant).

Meanwhile Elwert concluded from astrophysical arguments[26] that a lower corona temperature of about $6 \cdots 7 \times 10^5$ °K should be probable. In this case the short wave radiation would almost disappear and the thickness would be reduced. (In Fig. 5, the broken line is obtained when the radiations with $\lambda < 50$A are neglected).

One possible test of the theory is the influence of solar activity. This influence is rather important (Fig. 5). Elwert[26] obtains a correct value from the density variation of the solar corona.

4. CONCLUSIONS

There is no doubt that Elwert's hypothesis is attractive. Starting from solar data, which seems to be rather well established, he calculates almost exactly the shape and intensity of *E* layer ionization. It seems highly probable that the most important part of this ionization comes from x-rays.[27]

On the other hand, dissociation of oxygen certainly exists, and absorption data do not completely exclude ultraviolet radiation of 1000A from reaching the altitude of 120 km. Perhaps an extra radiation of this wavelength could be responsible for the stratifications of the *E* layer, like *E*2. But there is yet another unsolved question for this hypothesis of preionization, i.e., whether its effective cross section is sufficiently high.

We agree with Choudhury, that perhaps two different ionization processes could exist for the altitude of the *E* layer. Some sunrise effects could be better understood with this assumption.[28] However, contrary to this author's opinion, we would consider ionization by x-rays as the more important process, controlling the normal features of the *E* layer.

It seems that the rather complicated structure of ionization in the *D* and *E* regions must be attributed to several different absorption processes. As it is now known that turbulence and winds are normal features at the height of the *E* region, future theories of layer formation must take account of this influence.

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[22] E. G. Schneider, J. Opt. Soc. Am. **30**, 128 (1940).

[23] H. Siedentopf, Naturwiss. **35**, 289 (1948).

[24] The variation is obtained from experimental values of different authors; in the range 80···310 km the interpolation formula is $\log\alpha/\mathrm{cm}^3\ \mathrm{sec}^{-1} = -8.4 + 0.37\zeta + 0.68\zeta^3$, $\zeta = (190\ \mathrm{km} - Z)/100$ km. Details will be published later.

[25] H. Kulenkampff, Ann. Physik **79**, 97 (1926).

[26] G. Elwert, Z. Naturforsch. (to be published).

[27] In a recently published spectroscopic work on nitrogen ions, M. Dufay comes to similar conclusions [Ann. phys. **8**, 813 (1953)].

[28] E. Theissen, Naturwiss. 34, 371 (1947); R. Lindquist, J. Geophys. Research **57**, 439 (1952).