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Using Airglow Emissions for the Diagnostics of Some Magnetospheric-Ionospheric Influences

1. The Oxyen Emission λ 63000 Å

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1. Introduction

It has recently been established that the ionosphere is only part of a significantly larger plasma envelope around the Earth, which is called plasmasphere. More accurately, the ionosphere is the nearest to the earth-crust layer, where the absolute concentration of neutrals, electrons and ions is considerably higher than in the other regions. Considering the ionosphere in this way as part of the magnetosphere, we come to a new stage in the ionospheric investigations, i. e. to investigations of the dynamic couplings between the magnetosphere and the ionosphere. Now it is necessary to revise our previous concepts, and first of all that on the conditions of the disturbed ionosphere which is to be seen in connection with magnetospheric-ionospheric interactions. For example, we could show the ionospheric storms which were studied before by statistical methods mainly, in the mid- and low ionosphere. It has been realized in the past few years that a geomagnetic storm consists of separate elementary storms or substorms, and now it is possible to investigate and explain the physical nature of the ionospheric disturbances. The precipitation of corpuscules in the ionosphere was considered as a direct consequence of the solar flares, and not as a purely magnetospheric process caused by the flare.

Different methods are used in the diagnostics of the magnetospheric-ionospheric interactions, by which the conditions of the ionosphere and the magnetosphere are studied separately while at the same time we are looking for the relations between them. In general, we could classify these methods in two main groups. To the first group, that of ground methods, belong all classical investigations of the ionosphere and magnetosphere used during the last few decades. In the second group of methods, which may be called space methods, the investigations are carried out directly in space by equipment on rockets and artificial satellites. Direct measurements are thus taken of the structural parameters of the plasma concentrations of electrons, ions and neutrals, in addition to temperature measurements. Here belong also the measurements of the various dynamic characteristics such as drift, wind, diffusion, etc. Electric and magnetic fields in the plasma, as well as various other processes are also measured by space methods.

It should be pointed out, however, that the classification of these methods in two groups is a very conventional one. An essential part of the structural and dynamic parameters of the ionosphere and magnetosphere can be obtained independently by any one of the two methods. A typical example is the measurement of the electron density by ground methods and by various rocket and satellite methods.

We know that the investigation of the neutral optical emissions of the near-space plasma provides a vast amount of information about the complicated physicochemical processes which take place in this medium. In the auroral zone in particular, the investigation of the atmospheric emissions is the basic source of information for studying the interaction between the corpuscules and the ionospheric plasma.

The purpose of this paper is to show the opportunities offered by the investigation of the atmospheric emissions for discovering the magnetospheric-ionospheric relations, mainly as regards the subauroral regions — mid- and low latitudes. The aurorae will be discussed to the extent to which they are connected with the optical emissions over mid- and low latitudes.

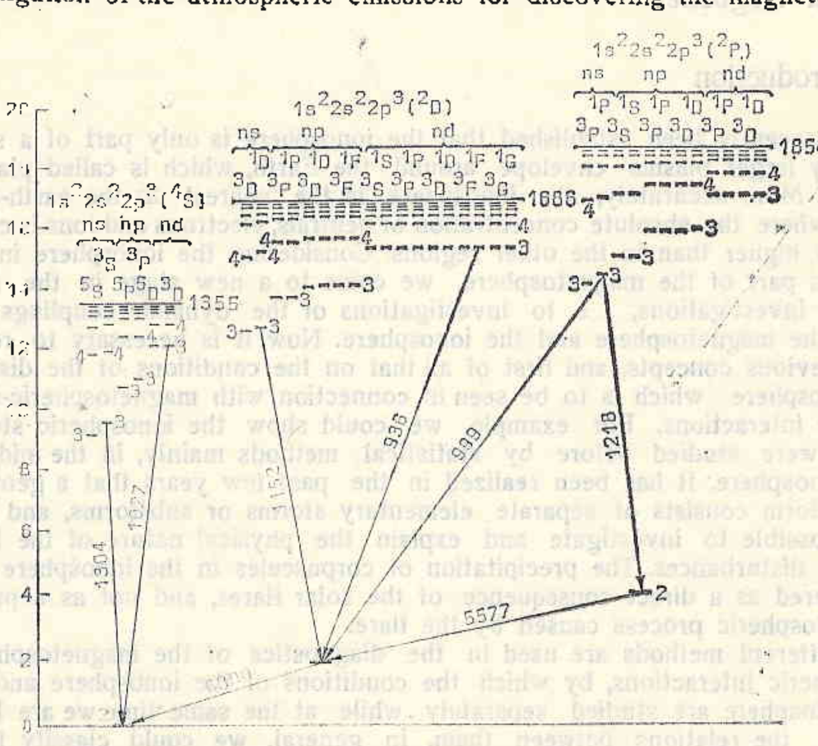

Fig. 1. Energetic terms of the oxygen atoms

2. Excitation of the Oxygen Emissions

As is well known, in the intermediate $E-F$ and F regions, i. e. that part of the ionosphere which is in direct contact with the magnetosphere, the oxygen atoms are the basic components of the plasma. For that reason, let us consider the ways of excitation of the oxygen atoms. Fig. 1 presents the diagram of the basic energetic terms of the oxygen. It shows that the nearest to the basic term (^3P) and, consequently, most easily excited terms are ^1D (energy of excitation 4.17 eV). The restoration of the atom from an excited state to the normal is achieved by the transition $^3P-^1D$, at which the red oxygen triplet λ 6300 Å, λ 6364 Å and λ 6391 Å is emitted, and the transition $^1D-^1S$ leads to the emission of the so-called auroral line with a length of 5577 Å.

2.1. The red oxygen line λ 6300 Å

The first line of the triplet with a length of 6300 Å is significantly more intensive compared with the second and third lines, and it is the one usually quoted. This line, called nebular line because of its large propagation in the nebulas, holds an important place among all airglow emissions. (Later on we shall explain its popularity.) The basic mechanisms leading to excitation of the term ^1D and, consequently, to emission of λ 6300 Å have been thoroughly treated in [1—6]. These mechanisms are the following:

2.1.1. By chemical reactions

The two basic reactions playing an essential role in this process are the dissociative recombinations of O_2^+ and NO^+:

$$(1)\qquad O_2^+ + e \longrightarrow \begin{array}{l} O(^1D)+O(^3P) \\ O(^1S)+O(^3P) \\ O(^1D)+O(^1D) \\ O(^1D)+O(^1S) \end{array} \qquad \alpha_D(O_2^+)$$

$$(2)\qquad NO^+ + e \longrightarrow \begin{array}{l} O(^1D)+N(^4S) \\ O(^3P)+N(^2D) \\ O(^3P)+N(^4S) \end{array} \qquad \alpha_D(NO^+)$$

The above reactions reveal that the dissociative recombination of O_2^+ is considerably more productive than that of NO^+. It has been theoretically and experimentally established that at each act of recombination of O_2^+ at least one of the oxygen atoms has a term ^1D, while the efficiency of reaction (2) is by one order lower, i. e. at ten recombinations of NO^+ at least one oxygen atom has a term ^1D.

The dissociative recombinations (1) and (2) have a very high rate. The rate constant of the first reaction $\alpha_D(O_2^+)$ is equal to 2×10^{-7} cm^3 s^{-1}, that of second reaction being 4×10^{-7} cm^3 s^{-1} [7]. Naturally, at such high rates of dissociation of O_2^+ and NO^+ the reserves should be depleted, but this does not actually happen. This situation explains the great importance of the ion-exchange reactions in the physics of E and F ionospheric regions, by which the stocks of molecular ions are continuously replenished.

$O(^1D)$ can be obtained also at triple collision, i. e. at a reaction of the following type:

(3) $$O(^3P)+O(^3P)+O(^3P) \longrightarrow O(^1D)+O_2,$$

but the above reaction is not very probable in reality because of the need of very high absolute densities of O in the $E-F$ and F regions which actually do not exist.

The reaction

(4) $$N(^2D)+O(^3P) \longrightarrow N(^4S)+O(^1D)$$

plays an essential role in the deactivation of the excited nitrogen whose life-time, before emitting, is about 26 hours. On the other hand, the quantity of $N(^2D)$ is small, and this leads to insignificant production of $O(^1D)$ by this reaction.

The same refers to the reaction:

(5) $$O^+(^2D)+O(^3P) \longrightarrow O^+(^4S)+O(^1D),$$

which is very effective at high altitudes.

2.1.2. Dissociation of O_2 according to the reaction:

(6) $$O_2(X^3\Sigma_g^-)+h\nu \longrightarrow O(^3P)+O(^1D).$$

The solar ultraviolet quantum taking place in this reaction is from the Schumann-Runge's continuum. Naturally, this reaction is valid only when the upper atmosphere is lightened directly by the Sun.

2.1.3. Direct electron collision

(7) $$O(^3P)+e \longrightarrow O(^1D)+e.$$

An essential part of the red line emission is emitted by the above mechanism, mainly during the day. This mechanism plays a definite role in some extreme cases during the night pre-dawn enhancement, SAR arcs, etc.

Let us see which electrons could take part in reaction (7) for the excitation of the term ^1D. No doubt, these electrons should have energy $E>2$ eV. In Fig. 2 the number of the atoms $O(^1D)$ are taken from [26], which number could be produced by one electron with energy E, at different values of the parameters of the fractional ionization $R=N_e/[O]$.

Let us now see where in the ionosphere could there appear electrons with energy in the range of $2\div100$ eV.

a) Photoelectrons. The observations show that the essential part of the day emission of λ 6300 Å is due to excitation by ambient photoelectrons, produced in consequence of the absorption of the short-wave solar radiation. At certain particular conditions the photoelectrons play a role during the night as well. For example, at mid-geomagnetic latitudes in winter, the intensity of the red line in the north hemisphere shows a sharp increase before the local dawn. This phenomenon, observed for the first time by Barbier in 1959 [3], was interpreted by Cole [8] as an effect of the photoelectrons arriving from the magneto-conjugate regions (MCR), where the Sun has already lightened the local ionosphere.

b) Superthermal electrons. The energy of these electrons is more than 2 eV. At daylight conditions, the high-energy end of the Maxwell distribution of the electrons is passing to and melting with the spectrum of the photoelectrons. During the night an insignificant part of the ambient electrons possess energy of over 2 eV. No doubt, this small part and the curve of the Maxwell distribution depends on the electron temperature T_e. The higher the T_e, the higher the contribution of the local thermal electrons to the excitation of λ 6300 Å. Let us note here that it is precisely by the superthermal electrons that some magnetospheric influences on the ionosphere are achieved, as can be detected by the red line. The heating of the ambient electron gas can be achieved by Cole thermal conductivity along the field lines, by dissipation of the energy in the F-region of iono-cyclotron waves generated in the magnetosphere, and by some other ways.

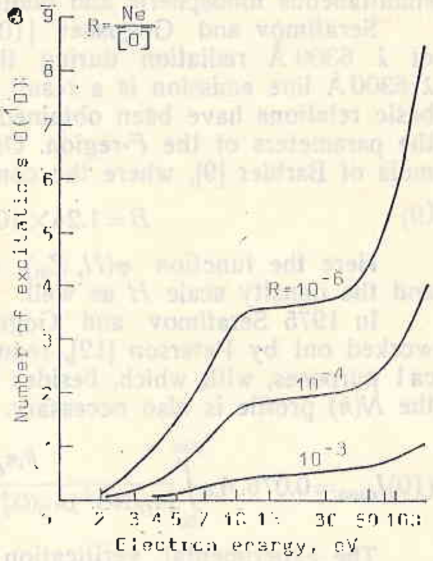

Fig. 2. Excitation of $O(^1D)$ by electrons

c) Secondary electrons obtained at the precipitation of electron and proton fluxes.

It is well known that the precipitating electron and proton fluxes from the magnetosphere provoke ionization of the atmospheric components. The secondary electrons obtained in this way take part in the elastic and non-elastic collisions, causing the rise of the neutral and ion temperature, and to a higher degree, that of T_e. At the non-elastic collisions, the vibrational terms of N_2 and O_2 are excited with higher efficiency, also that of ^1S and especially ^1D, for which a very small quantity of energy is necessary. In actual fact, at the aurora the excitation of the oxygen emissions is performed mainly by secondary electrons.

2.2. The red emission at calm conditions

The main generative mechanism of the λ 6300 Å line during the night is the dissociative recombination of O_2^+, according to reaction (1). Barbier and Glaume [9] obtained a semi-empirical relation between the intensity of the 6300 Å line and the ionospheric parameters at calm conditions, which is presented by the following formula:

$$I_{6300} = B(f_0F)^2 \exp.\left[-\left(\frac{h'F-200}{H}\right)\right], \tag{8}$$

where f_0F is the critical frequency of the layer F, $h'F$ is the height of the layer, H is the density scale, while B and C are constants determined at simultaneous ionospheric and photometric observations.

Serafimov and Gogoshev [10] presented in 1972 a generalized theory of λ 6300 Å radiation during the night. According to this theory, the λ 6300 Å line emission is a result of the dissociative recombination. Some basic relations have been obtained between the emission of this line and the parameters of the F-region. One of the relations is reduced to the formula of Barbier [9], where the constant B already has a physical meaning;

$$B = 1.24 \times 10^4 \, . \, k_1 [O_2]_{300} \varphi(H, Z_m). \tag{9}$$

Here the function $\varphi(H, Z_m)$ comprises the half-width of the layer Z_m and the density scale H as well.

In 1975 Serafimov and Gogoshev [11] improved the similar formula worked out by Peterson [12], reducing it to a convenient form for practical purposes, with which, besides the atmospheric model, the knowledge on the $N(h)$ profile is also necessary. This formula is:

$$I_{6300} = 0.076 . A . \varepsilon \int_{150}^{500} \frac{k_1 \alpha_D(NO^+) . \alpha_D(O_2^+) . [O_2] N_e^2 \, dh}{\{\alpha_D(NO^+) . \alpha_D(O_2^+) . N_e + \alpha_D(O_2^+) . k_3[N_2] + \alpha_D(NO^+) . k_1[O_2]\}(A + K[N_2])} \tag{10}$$

The experimental verification of formula (10), carried out by simultaneous ionospheric and photometric observations, has shown that it provides values about the intensity of the red line emission which are the nearest to those registered experimentally. By tracing the evolution of the connections between the red oxygen line and F-region parameters, our aim was to show that by the photometric observations of the λ 6300 Å emission during the night we can very well control the basic processes in the F-region. The accuracy of the photometric data exceeds that of the radiophysical measurements. For example, a change of 5–6 per cent, and even less, of the electron concentration in the F-region cannot be detected by vertical sounding, while changes of only 2 per cent in N_e can be detected by photometric measurements of the λ 6300 Å line.

2.3. *The red oxygen emission at geomagnetic activity*

2.3.1. Strong storms in the aurora zone

Observations of the red line emission, carried out over a period of many years at the Observatory of Stara Zagora, Bulgaria [4], at the Observatory of Abastumani, USSR [13] and at the Observatory of Zvenigorod, USSR [14] have shown that the mean night intensity of the red line emission, with the exception of the twilight periods, is within the limits of 20—100 R, under conditions of low geomagnetic activity ($K_p < 2$). The increase in geomagnetic activity leads immediately to a sharp rise in the λ 6300 Å emission intensity. Trutce [15] obtained a relation between D_{st} variations of the geomagnetic field and the abnormal rise in the red line intensity. This relation is the following:

$$(11) \qquad \log I_{6300} = \beta D_{st} + 2 \times 10^{-2} F - 3.17,$$

where F is the flux of the solar radio-radiation with a length of 10.7 cm (10^{-22} W/m²Hz), and β is a constant depending on the geomagnetic latitude. This relation makes it possible to estimate the total planetary flux of energy in the ionosphere by the intensity of the λ 6300 Å line, depending on the strength of the geomagnetic storm. For example, during the strong geomagnetic storm on 11 February 1958, at $D_{st} = 409\,\lambda$, the energy of the red line was about 300 erg/cm² s.

Let us note here that the above relation is valid for geomagnetic storms at which $D_{st} > 100\,\gamma$ and at geomagnetic latitudes of more than 40°. This important formula no doubt reflects a definite generative mechanism which is valid only for subauroral zones and also for a definite region of the magnetosphere. The action of this mechanism is insignificant during weaker geomagnetic storms ($D_{st} \leq 100\,\gamma$) and the observed increase in the intensity of the red line must be explained in another manner. The most probable cause for excitation of the 6300 Å line, at strong geomagnetic storms, is the heating of the F-region and the rise of T_e. In this case, as we have shown above, there is an increase in the quantity of the superthermal electrons exciting the 6300 Å line. We shall have, of course, electrons with energy over 4.16 eV which could excite the green oxygen line as well, but they would be few and, contrary to the assertion of Krassovsky [16], the green oxygen line should have a very low intensity. Our calculations show that the intensity of the red line, obtained by the thermal mechanism, should be by four orders higher than that of the green line. The same ratio has actually been observed during the geomagnetic storm on February 11, 1958, and this confirms the existence of the thermal mechanism. We must add, however, that the cause of the heating of the electron gas in this case remains unknown.

2.3.2. SAR-arcs

A full review of the observations of SAR-arcs and their generative mechanisms is given in [17]. In general, these arcs are observed over mid-latitudes (Fig. 3) at a height of about 400 km. Their length is several thousand kilometres and their width is several hundred kilometres. They have an intensity of between 100 and 1000 Rayleighs. The most important fact is that the red arcs are observed in that region of the atmosphere where the plasmapause is projected. We assume that the basic generative mechanism is related to the appearance of the ion-cyclotron waves in the zone where the asymmetric ring current is spread out in the plasmapause region. The dissipation of the energy of these waves in the F region leads to heating of the electron gas and to the corresponding glowing of the atmosphere by the red emission. The exact determination of the height (by vertical sounding) can provide very good information about the nature of these electro-magnetic waves, taking into consideration the fact that they transmit their energy to the electron gas depending on the free path of the electron.

2.3.3. Increase of the red line emission over mid- and low latitudes

The absence of a sufficient number of stations in the equatorial zone and in the low latitudes makes it impossible for us to assess exactly the behaviour of the 6300 Å emission during the geomagnetic disturbance. In general, the satellite observations have shown that at about 10—15°, on both sides of the magnetic equator, there exist regions (arcs) with elevated intensity of the red oxygen line. (These are the familiar regions of higher electron concentration related to what is known as the equatorial anomaly.) It is difficult to maintain that they are connected with the magnetospheric processes and with the ring current, and that they depend on the geomagnetic activity.

In 1973, through the observations carried out at the Bulgarian station of Stara Zagora, quasiperiodical oscillations of the intensity of the λ6300 Å line were discovered with an average period of 90 minutes during the main phase of a geomagnetic storm (Fig. 4) [18, 19]. Later on Vlassov and Romanovsky [20] pointed out that the observations at the Observatory of Stara Zagora were the first confirmation of the existence of the theoretically predicted oscillations with such period, which, in their opinion, are due

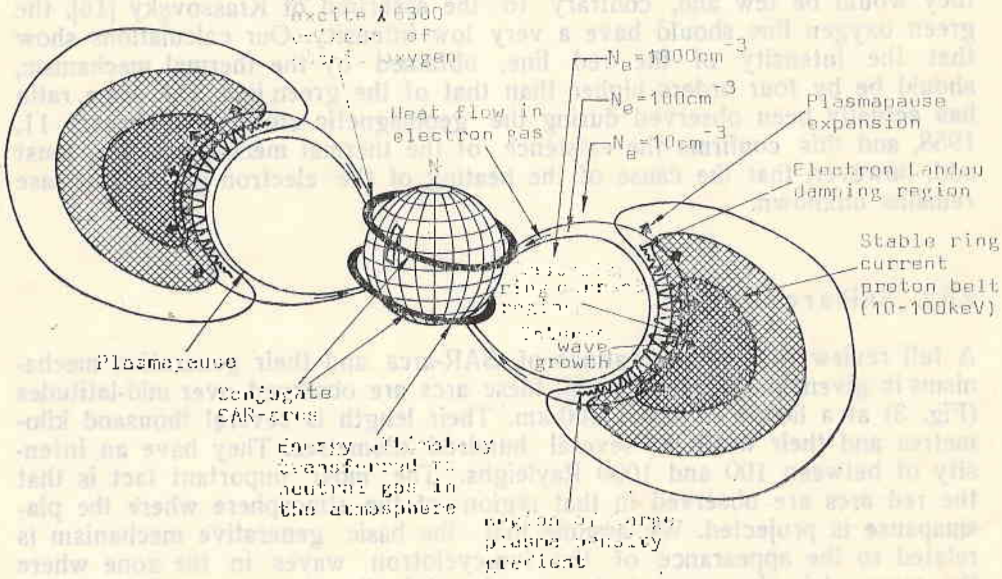

Fig. 3. Schematic diagram of the magnetosphere and the regions in which the SAR-arcs are excited

to changes in ion concentrations in the F region during the geomagnetic storm. Comparing the above observations of the atmospheric emissions with those of the geomagnetic field (at the station in the oval — Leirvogur and at the station of Panagyurishte), and also with the data from the ionospheric station of Sofia, Gogoshev, Serafimov, Gogosheva and Kazakov [21, 22] have shown that:

a) The time and the periods of the wave oscillations of the glowing are connected with the substorms in the polar region.

b) The height of the F-layer has pulsated synchronously with the substorms.

c) As a consequence of that, the dissociative recombination, by which the observed oscillations could be explained quantatively, has been changed.

d) The assumption that electric fields with intensity of 5—10 mV/m are generated during the substorm in the mid-latitudes, tallies very well with the experimental data.

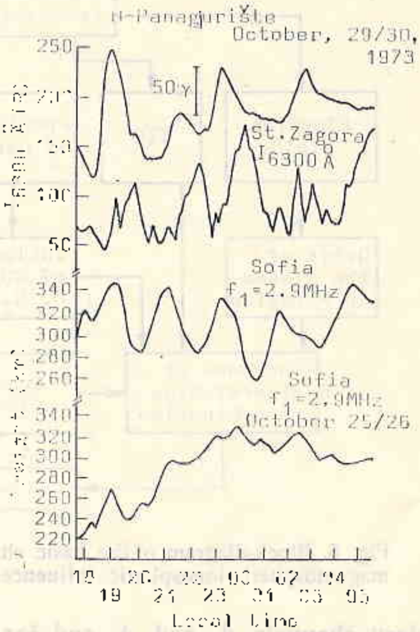

Fig. 4. An example for substorms in the mid-latitude ionosphere

Another example of emission, increase over the mid-latitudes is the case which occurred on September 18/19, 1974. After a comparatively strong geomagnetic storm during the period of 14—17 September, a normalization of the geomagnetic field was observed. During the evening hours on September 18/19, however, there was a single and isolated sub-storm. About one and a half hours after that the Observatory at Stara Zagora registrated a sharp increase of the intensity of the λ 6300 Å line reaching 600 R. At the same time, the ionograms at the station in Sofia showed the presence of ionospheric heterogeneity, which strongly intensified the dissociative recombination and hence the glowing of the red line [23]. It is assumed that the generator of these moving heterogeneities is located in the polar region, perhaps it coincides with the auroral oval and increases during geomagnetic activity [24].

3. Conclusion

The influences of the magnetosphere on the mid- and low latitude ionosphere which culminate in a rise of the red oxygen line intensity as a final result, are presented in Fig. 5. It shows that the increase in the λ 6300 Å line can be achieved through four channels which we denote by the letters A, B, C, D. Naturally, with one single observation only of the λ 6300 Å line it is impossible to solve this system of equations with four unknown quantities. Therefore, other observations are to be carried out, parallel with the observations of the red line. First, we must carry out ionospheric observations of the F region, by which several structural parameters can be measured, such as N_e, for example. Through N_e we could immediately control the most important channel A (dissociative recombination). Let us assume that the influx of λ 6300 Å emission is passing through the channel A. This channel consists of four secondary channels (A_1, A_2, A_3, A_4). The measured ionospheric data are quite enough for comparison and control of the secon-

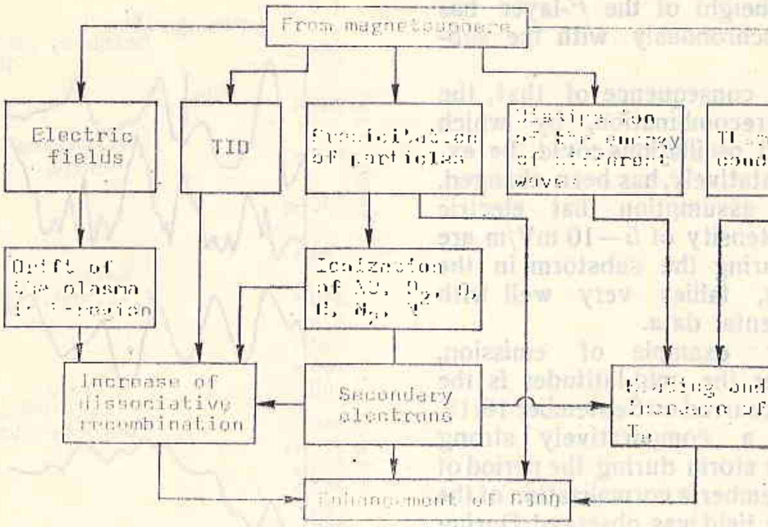

Fig. 5. Block-diagram of the basic channels for excitation of the λ 6300 Å line under magnetospheric-ionospheric influence

dary channels A_1 and A_2 and for their sufficient discrimination at the same time. If channels A_1 and A_2 are not operating we must check the connections A_3, A_4 and B, C, D as well. No doubt, there exists a definite connection between channels B, C, A_3 and A_4 which is unknown. We only know that the channels B, C, A_1 and A_2 are operating simultaneously. By way of a qualitative explanation, we could only say that A_1, A_2 and C, for mid-latitudes, are much weaker than B.

The channel C can be controlled in the following way: It is well known that the precipitation of corpuscules leads to ionization of N_2 and, at the same time, to the excitation of the first negative system of N_2^+. By observations of the lines λ 3914 Å or λ 4278 Å we can provide a qualitative estimation of the flux of particles and, consequently, of the influx into the channels B, A_3 and A_3. Additional information for channel B can be obtained by parallel observations of some bands of N_2 and O_2, which are excited only by secondary electrons. Consequently, the unknown channel is only D, which can be determined by observations as the difference between the observed values of λ 6300 Å emission and the estimated influx of A, B and C. This difference can immediately give us information about the electron temperature T_e, by using the graph in Fig. 6 [25].

In addition to the analysis given in section 3, the use of a photometric station can be recommended for the ground diagnostics of the magnetospheric-ionospheric influences by the atmospheric emissions, in which station the atmospheric emissions λ 6300 Å, λ 3914 A and one of the bands of N_2

or O_2 are measured. In addition, the use of an ionospheric station also is recommended, as it can give the basic structural parameters of the F region, with the same time resolution.

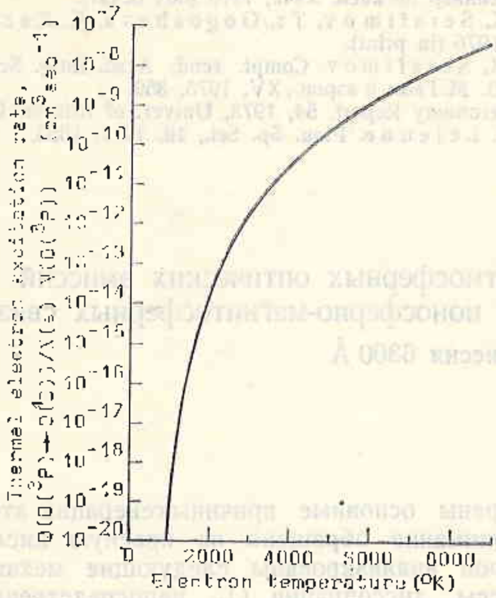

Fig. 6. Excitation of the red oxygen emission depending on the electron temperature

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Использование атмосферных оптических эмиссий для диагностики ионосферно-магнитосферных связей

1. Кислородная эмиссия 6300 Å

М. М. Гогошев

(Резюме)

В работе рассмотрены основные причины генерации атмосферных эмиссий. Особенное внимание обращено на красную кислородную линию 6300 Å, для которой анализированы следующие механизмы генерации: химические процессы, диссоциация O_2, непосредственные электронные удары и диссоциативная рекомбинация. В работе также рассмотрены причины излучения линии во время магнитосферных смущений и в авроральных красных дугах. Сделано предложение для диагностики ионосферно-магнитосферных связей посредством измерения атмосферных оптических эмиссий.