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Space Plasma Emissions — Indicator of Magnetospheric-Ionospheric Processes

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Introduction

Airglow investigations were initiated at the beginning of this century after the experiments of the English astronomer Simon Nucomb, related with measurements of sky brightness. He was the first to make the conclusion that the sum brightness of stars, galaxy, zodiac light and other sources is not sufficient to interpret the observable night glow. These experiments laid the foundations of a new scientific field, intermediate between astronomy and geophysics. Using mainly astronomical methods orientated to geophysics, the airglow intestigations, especially during the 50s of this century, largely contributed to the more complete understanding of the physico-chemical processes of the so-called 'low-temperature surrounding space plasma.'

We may summarize that this type of measurement provide abundant information on:

1. neutralizing processes in the ionosphere;
2. availability of minor constituents and their distribution into the atmosphere;
3. wide range of aeronomical reactions, their velocities and temperature dependence;
4. interaction between ionized and neutral components;
5. magnetospheric effects on the ionosphere, both in auroral and at mid- and low latitudes.

These studies provide important information on many other processes and phenomena which cannot be efficiently investigated mainly through the classic radiophysical methods. Fig. 1 illustrates a general diagram of the solar energy transformation (irradiation and particles) into a glow as a finite product [25].

The Bulgarian contribution to the airglow studies started with K. Serafimov's theoretical works in the 60s [1, 2, 3]. They were substantially devoted to the interpretation of the green oxygen line behaviour and mainly to its aroundmidnight maximum.

The first experimental observations and the initiation of systematic, various airglow investigations in Bulgaria had started later, in 1968 [4]. Different types of photographic and electrophotometric instruments were developed at the

Observatory of Stara Zagora. Various techniques for spatial and spectral study of the optical emissions were developed here along with stationary airglow facility [5] successfully used not only in the Bulgarian observatories, but also in India [6], Cuba [7] and Guinea, Konakry [8].

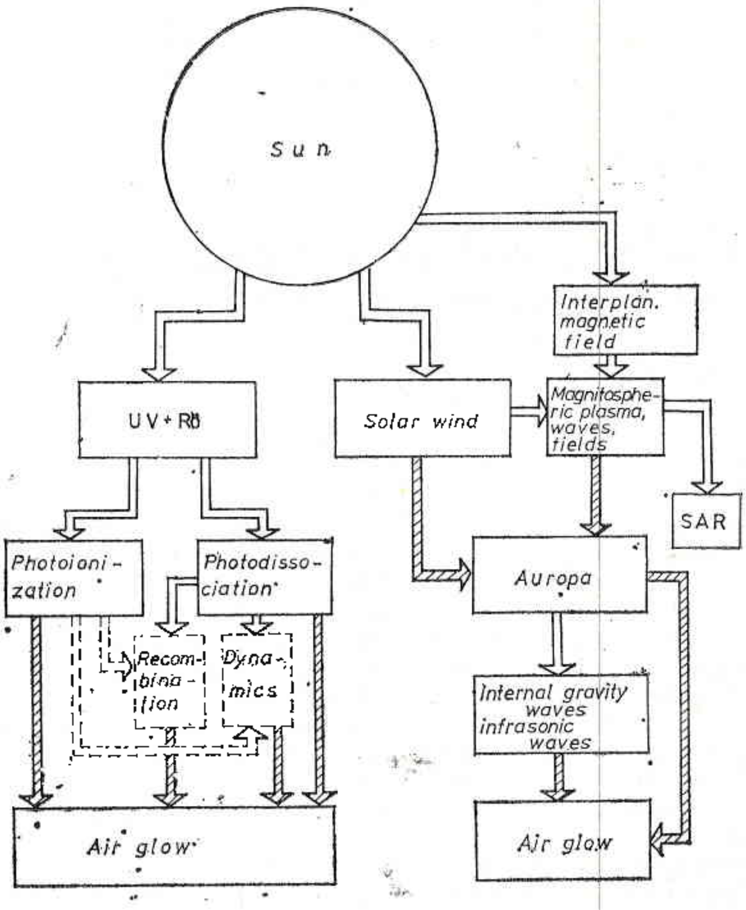

Fig. 1. Scheme of the dissipation of solar energy in the upper atmosphere

The first Bulgarian airglow instrument was launched into space in 1977 This was an electrophotometer aboard the VERTICAL-6 rocket, developed for the measurement of the vertical profiles of various optical emissions [9]. Successful experiments were carried out on VERTICAL-7 and 10 and on the two Indian rockets CENTAUR-II B [10].

A 6-channel electrophotometer was launched aboard INTERCOSMOS-19 in February, 1979 to measure the main spectral emissions in the upper atmosphere in the visible spectral range.

Successful experiments were carried out with tilt filter photometers, operated by cosmonauts aboard SALYUT-6 and SALYUT-7 stations. These studies, along with the various optical experiments aboard the INTERCOSMOS-BULGARIA-1300 satellite, launched on August 7, 1981, substantially contributed to the understanding of the physical processes in the surrounding space plasma, some of which will be discussed here.

Airglow and nighttime F-region behaviour

Some scientists had originally concluded in the 40s that the behaviour of the red oxygen line with a wavelength of 630 nm correlated with some parameters of the nighttime F-region of the ionosphere. Nevertheless, only at the beginning of the 50s D. Barbier [11] suggested a semi-empirical formula for the relationship between the measured integral intensity of the emission and the F-layer height and its critical frequency. This formula has the form of:

$$I_{630}=K(f_0F)^3e^{-\frac{h'F-200}{H}}+C. \tag{1}$$

Here K and C are two constants, depending both on the situation of the observational station and on the concrete observation conditions. On the basis of a more advanced theory for the ionospheric processes in the F-layer and assuming that:

a) the main generative mechanism of λ 630 nm during nighttime is the dissociative recombination of the O_2^+ ions;

b) they are obtained through exchange reactions between O^+ and O_2;

c) the density of O_2 beyond 200 km varies after the exponential law;

d) the electron density around the layer maximum is approximated by a parabolic function, and above this by an exponential, Serafimov and Gogoshev have obtained [12, 13] a much more accurate dependence than Barbier, where part of the empirical constants acquire also physical content. This is as follows:

$$I_{630} = K_C(f_0F)\,\varphi(H,\, Z_m)e^{-\frac{h'F-200}{H}}+C \tag{2}$$

Here, similar to (1), the critical frequency of the F-layer is denoted by f_0F, $h'F$ being the virtual height of the F-layer, H is the scale height of the neutral atmosphere and $\varphi(H,\, Z_m)$ is the function describing the geometry of the F-layer.

Very important result is the fact that the constant K of Barbier's formulae acquires the following physical meaning

$$K_C=1.24.10^4K_{exc}\,[O_2]_{200}, \tag{3}$$

where K_{exc} is a constant of the velocity of the exchange reaction $O^++O_2\rightarrow O_2+O$ and $[O_2]_{200}$ is the oxygen molecules density at a level of 200 km. Obviously, when through a series of experimental observations on I_{630} the numerical value of K_C is determined, then it is possible to obtain such an important parameter as $[O_2]_{200}$.

Investigations on topside F-layer portion through optical emissions

Few are the optical emissions, irradiated into the topside F-region. Two of the most substantial are the oxygen λλ 130,4 nm and 135,6 nm. Situated into the region of the so-called vacuum ultraviolet, they are inaccessible to direct measurements from the earth surface. Regardless to this, their great informability was demonstrated in the few rocket and satellite experiments performed.

Serafimov devoted series of theoretical publications [14-17] to the theory of excitation and glow of these two spectral lines. Further, this fundamental theory was accompanied with various experimental works, based on direct measurements of the intensity of the two lines aboard the INTERCOSMOS-BULGARIA-1300 satellite [18-21].

Serafimov assumes the following generative mechanisms into the analysis of the λ 130,4 nm excitation:

a) radiative recombination of O^+ ions with electrons;

b) ion recombination of positive and negative atomic ions in the F-region (O^+ and O^-);

c) collision excitation by soft electrons (of energies above 9 eV).

Most productive of these mechanisms is the first one, occuring in the topside F-region.

Each of these generative mechanisms, the regions of predominant effect of each versus the others and their quantity values were estimated by Serafimov in his works. He founds in [22] the following complete expression for the bulk velocity of the emission of $I_{130,4}$ into the F-region of the ionosphere

$$\frac{dI_{130,4}}{dh} = C_{130,4}K_q\left\{\alpha_{e,1304}\cdot N_e\cdot[O^+]+\alpha_{i,130,4}\cdot[O^-]\cdot[O^+] + \int_g^{E_r}\sigma_{130,4}\cdot B\cdot N_e\cdot e^{-P_1Ee}\,dEe\right\}, \tag{4}$$

where K_q is the quenching coefficient of deactivation of the excited oxygen term; $\alpha_{e_1\,130,4}$, $\alpha_{i,\,130,4}$ are the velocity constants of the radiative and ion recombinations of O^+ with electrons and O^-ions, respectively, $\sigma_{130,4}$ is the cross section of the electron collision of O with electrons at output $O(2p^33s^3S_1^0)$; E_r is the upper boundary of the integral by energies which in Serafimov's opinion may be sufficiently assumed up to 100 eV; P_1 is an index in the exponential of the electron flux spectrum, BN_e is the amount of electrons from the flux of energy $E_0=9$ eV, wherefrom the excitation of the triplete around λ 130 nm starts with electron collision. Serafimov found complete expression for the emission vertically (zenith intensity) of λ 130,4 nm integrating by the height h, under approximations of the altitudinal distribution of the subintegral functions deduced by him. This expression is to be properly compared with the experimental data.

Successfully using the models for the neutral components distribution into the upper atmosphere, Serafimov considered the increase of λ 130,4 nm intensity due to its multiple resonance scatter from the atmospheric components. In the result to this the observable intensity of λ 130,4 nm depends on the height of the satellite, and of the UV instrument, respectively. This effect is significantly reflected on the measured ratio of $I_{130,4}/I_{135,6}$ which will be discussed further on.

Similar procedure was made to analyse the other ultraviolet emission of a length λ 135,6 nm. Serafimov defined that the output term $O(2p^33S^5S_1^0)$ of this emission had the same generative mechanisms as that of λ 130,4 nm [23]. Similar to (4) is the expression for the bulk velocity of λ 135,6 nm emission.

Serafimov obtained for the bulk velocity of emission for both lines

$$\frac{\dfrac{dI_{135,6}}{dh}}{\dfrac{dI_{130,4}}{dh}} = \frac{\varphi_1(h)N_e+\displaystyle\int_g^{E_r}\sigma_{135,6}\,B_1\,e^{-P_1E_e}\,dE_e}{C_{1304}(h)\left[\varphi_2(h)N_e+\displaystyle\int_g^{E_r}\sigma_{130,4}\,B_1\,e^{-P_1E_2}dE_2\right]}. \tag{5}$$

$\varphi_1(h)$ and $\varphi_2(h)$ in this expression are linear functions of $\alpha_{e_1\,135,6}$ and $\alpha_{e_1\,130,4}$ of $R_e=\frac{[O+]}{N_e}$ and of $\lambda_0=\frac{[O-]}{N_e}$.

The examination of the bulk velocity ratio was not accidental, since as we have shown above, the zenith intensity of λ 130,4 nm depends on the distribution and density of neutrals, as well as on the area of the emitting region.

Global diagnostics of ionospheric parameters through optical data only

Bittencourt and Tinsley were the first [24] to draw attention to the fact that the intensity of the red oxygen line is very sensitive and depends on the height at which is located the maximum of the nighttime F-layer. Simultaneously, similar **is the behaviour and the dependence** on the maximum electron density of λ 135,6 nm. The authors were the first to suggest the idea to diagnose the specifically important parameters h_mF and N_mF through the combined measurements of these two lines.

Based on the thorough studies of λ 630 nm and of the two ultraviolet lines λλ 130,4 nm and 135,6 nm made by the Bulgarian scientists, K. Serafimov suggests a more complete and correct interpretation of the combined use of the two airglow emissions for the determination of these important ionospheric parameters [17]. While Bittencourt and Tinsley used semiempirical dependence for the determination of the $I_{135,6}$ dependence on N_mF, Serafimov defines the same based on formulae deduced by him for $I_{135,6}$ emission and with the use of the international reference models IRI. The latter are used to give the shape of the profile only, while the maximum value of the electron density N_mF is given by the measured $I_{135,6}$. This dependence is as follows:

$$I_{135,6}=1{,}19\,.\,10^{-12}A_0\,.\,A_1^2(N_mF)^2e^{-PA_0}\left(\frac{e^{-PA_0}}{S}-\frac{e^{-PA_0X_2}}{5X_2^5}\right.$$
$$-\frac{PA_0}{20}\left\{e^{-PA_0}-e^{-PA_0X_2}\left[1-PA_0\left(\frac{1}{3X_2^2}-\frac{PA_0}{6X_2^2}+\frac{P^2A_0^2}{6X_2}\right)\right]-PA_0e^{-PA_0}\left[\frac{1}{3}-\frac{PA_0}{6}\right.\right.$$
$$\left.\left.+\frac{(PA_2)^2}{6}\right]+\frac{(PA_0)^4}{6}\left[E_1(-PA_0X_2)-E_1(-PA_0)\right]\right\}. \qquad (6)$$

In this rafher long, but very suitable for computation expression, the parameters A_0, A_1, A_2 and P are taken from the IRI models for each concrete case, $X_2=1+\frac{h-h_m}{A_0}$, and E_1 is generally adapted denomination of the integral-exponential function.

Formula (6) in combination with h_mF determined through λ 630 nm measurements, enables the determination of N_mF practically in any point above the earth surface, through the use of a relatively cheap and accessible satellite technique, i. e. with the incorporation of optical equipment. (Here the alternative possibility is considered — the use of a satellite ionosonde — a very expensive technique).

Verification of compatibility of neutral and ionospheric models through airglow observations

As it is known, the first models for the distribution of the neutral components in the upper atmosphere were built up at the beginning of the 60s (UR standard atmosph., CIRA-55, Jacchia-71, etc.). Data mainly from the measured satellite resistance were used for the purpose, resulting from shortening of the satellite orbit and from mass-spectrometric data, too. These models were improved regularly and after CIRA-75 and Jacchia-77, the most precise one at the moment is the MSIS model.

The ionospheric models composed by Prof. Rawer's group within the scope of COSPAR and URSI were initiated in 1975 [27]. They are also subject to continuous improvement.

Many experiments on the simultaneous use of neutral and ionospheric models for practical geophysical computations have shown certain incompatibility and necessity of improvement. Many Bulgarian publications of Serafimov, Gogosheva, Gogoshev and others revealed a very accurate criterion for such compatibility [26, 28, 29]. The excitation and the emmission of the red oxygen line is used for the purpose — λ 630 nm in nighttime ionosphere. Many studies, including Bulgarian, have shown that in a calm geomagnetic situation the following aeronomic reactions are basic for the formation of λ 630 nm at night-(time of the F-region

$$O^+ + O_2 \rightarrow O_2^+ + O\,; \tag{7}$$

$$O_2 + e \rightarrow O(1_D) + O(3P). \tag{8}$$

The first of these reactions (7) is limiting to the emission velocity. Here the ion component (O^+) participates in ion-exchange reaction with the main neutral O_2. Thus, we may write the following expression for the exchange velocity of emission:

$$\frac{dI_{630}}{dh} = \frac{\varepsilon_1 A_{630} \gamma_1 N_m F \,.\, S(h)}{A\left[1+\frac{d(h)}{A}\right][1+B(h)]}\,. \tag{9}$$

In this formulae, ε_1 is the quantum output of reaction (8); recent satellite measurements yield $\varepsilon_1 \approx 1{,}33$; $A_{630} = 0{,}069\ s^{-1}$; $A = 0{,}0091\ s^{-1}$; $S(h)$ is profile-shaping factor; $N_m F S(h) = N_e(h)$ is the local electron density, and $d(h)$ and $B(h)$ are the deactivation factors, depending also on the altitudinal distribution of the neutrals. Through the integration of the two sides of equation (9) by the height h we obtain a dependence of the column emission (zenith intensity) in dependence of the distribution of N_e and O_2 with the height. The latter are taken from IRI and any neutral model, respectively. Experimentally comparing the measured zenith intensities with the theoretical values thus defined, the compatibility of ion and neutral models is estimated.

In the publications of Serafimov and others a thorough study is made on comparison between theory and observations on the nighttime emission of λ 630 nm, performed in the observatory of Stara Zagora. It is found that the model computations give intensities at midnight of the order of several Reileighs for low solar activity, while the actually measured ones are 20-30 R. The use of various neutral models (for example Jacchia-77 and MSIS) and IRI provide the same results. This fact, as well as some other criteria, contributed to the conclusion that the IRI-models at low solar activity should be corrected, since the electron density deduced by them is lower than the actual one.

Conclusion

The study of the optical emissions in the last decade contributed significantly to the clarification of the sophisticated complex of solar-terrestrial interaction as a whole, and of the magnetospheric-ionospheric processes in particular. A lot of Bulgarian publications — theoretical and experimental — ground-based, rocket and satellite, contributed to the more thorough penetration and study of the energy transfer in the surrounding space environment, which together with its fundamental nature is of definite practical importance.

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Излучение космической плазмы — индикатор магнитосферно-ионосферных процессов

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(Резюме)

Сделан обзор основных физико-химических процессов, протекающих и приводящих к возбуждению и излучению оптических эмиссий в космической плазме. Исследование этих излучений даст важную информацию о нейтрализационных и ионизационных процессах, о скоростях аэрономических реакций, о плотностях малых составляющих, о взаимодействии ионизированных и нейтральных компонент, о воздействии магнитосферы на ионосферу Земли. Конкретно показано участие болгарских ученых в этих исследованиях, начавшихся работами К. Серафимова с начала 60-х годов. Подробно рассмотрены результаты излучения надмаксимумной части Г-области при помощи оптических эмиссий, а также улучшения международных ионосферных и нейтральных моделей и диагностики магнитосферно-ионосферных связей.