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First Results from Ionospheric Airglow Measurements Carried Out in Cuba

M. M. Gogoshev, S. K. Chapkunov, J. S. Gonzales,
L. Palacio, G. Hill

Introduction

It is known that there is a large number of physico-chemical processes which bring the different atmospheric components into a state of excitation. A considerable part of the day airglow is emitted as a result of photoionizational excitation. For instance, the photoionization of the oxygen molecule can bring to excitation one or two oxygen atoms:

$$O_2 + h \text{ (from Sun)} \rightarrow O^* + O. \tag{1}$$

The atomic and molecular excitation of the upper atmosphere can also be provoked by collisions with the precipitating particles from the magnetosphere in a reaction of the following type:

$$O + e \rightarrow O^* + e. \tag{2}$$

The electron in the left part of the expression (2) possesses energy slightly superior to the thermal energy of the electrons in the ionospheric plasma. The atomic or molecular excitation level depends on the electron or proton energy as well as on the cross-section of the interactions.

The ionospheric subthermal electrons, the so-called photoelectrons obtained during the photoionizational process, can also take part in reaction (2) during the day (*E*- and *F*-regions).

Particularly important is the contribution by the recombination aeronomical reactions, primarily by the so-called reactions of dissociative recombinations of the molecular ions in the irradiational ionospheric processes. The main reactions of that type are:

$$\begin{array}{llll}
(3) & O_2^+ + e & \rightarrow O^* + O & \alpha_D(O_2^+) \\
(4) & NO^+ + e & \rightarrow O^* + O & \alpha_D(NO^+) \\
(5) & N_2^+ + e & \rightarrow N^* + N & \alpha_D(N_2^+)
\end{array}$$

These reactions are of an order of 10^{-7} cm^{3}s^{-1} [1, 2] and their velocity constants are written at the right-hand side of the expressions.

Reactions (3), (4) and (5) operate diurnally and they play a particularly important role during the night, when there is no ionizing source. That is how the concentrations of electrons and of molecular ions are determined by these reactions. The quick disappearance of the molecular ions during the night is compensated on account of the ion-exchange reaction of the following type:

(6) $O^+ + O_2 \rightarrow O_2^+ + O$ velocity of K_2 according to [3].

In the ionosphere the aeronomical reactions of type (7) are around fifty in number or more. A review of these reactions in the ionosphere is offered in greater detail in [1-6] and in some other papers.

The examples given until now refer predominantly to the oxygen atoms and molecules, because they play the most important role in the *F*-region.

The irradiation of the atmospheric components can be obtained by the re-emission of some lines and bands of the solar light. This phenomenon takes place mainly during the twilight but essentially it has no considerable effect on the airglow processes of the upper atmosphere.

It could safely be maintained that the airglow emissions from the aurora and from the upper atmospheric layers above the middle, low and equatorial latitudes are practically the same. The difference lies mainly in the intensity and in the fact that the polar emissions operate according to reaction (2), while at other latitudes reactions (1), (3), (4), (5) and (6) are valid. The theory of airglow emissions through the aurora and upper atmosphere can be found in [1].

Notwithstanding the fact that considerable progress has been made in the study of the upper atmosphere airglow and that there are many publications on this problem which show the connection between ionospheric processes and airglow, there is still no unanimous opinion on the nature of these connections. This is due mainly to the fact that until now the airglow emissions have been studied n an isolated manner. In such an eminent publication on atmospheric emissions s [1], these connections are treated mainly as being statistical in character, while one of the latest monographs published in 1975 on the ionosphere [7] contents itself with the description of the airglow-ionospheric connections obtained during the 1960's.

The purpose of this paper is to describe the first measurement results from the airglow emissions of the upper atmosphere carried out in Cuba and to show the connection existing between some of them and the ionospheric parameters measured there.

Selection of Measuring Emissions, Measuring Techniques and Equipment

In order to study the connections between the airglow emissions of the upper atmosphere and the ionospheric parameters, the best way is to choose emissions from the *E*- and *F*-layers. This is determined mainly by the presence of a relatively small number of atmospheric components and by the absence of complex molecular ions (e. g. negative ones). Furthermore, in order to reveal the physical connection of these parameters it is most convenient to choose the emission lines because, as it will be seen later on, they are best suited to photoelectric measurements.

The following emissions were selected for the purpose: First is the red oxygen line with λ 6300 Å of longitude (in fact this is the double 6300-6364). This line is emitted in the *F*-region. Second is the green oxygen line λ 5577 Å. It is emitted mainly in the *E*-region (80-120 km), though about 15-20 per cent of its intensity is emitted in the *F*-region [8]. The third is one of the lines of the first negative system of the N_2^+ molecule. Its longitude is 4278 Å. The negative system is excited only by direct particle precipitation, and this provokes simultaneous ionization and excitation. Therefore, when controlling the emission, we can study the precipitation particle effects on the upper atmosphere.

In order to establish the quick variations of these emissions, which is particularly important for the phasic processes in the ionosphere, we have selected the two-filter photoelectric method. As we know, electrophotometry enables us to obtain a very high temporal resolution and, on the other hand, the sensitivity of this technique greatly exceeds that of the photographic method.

The two-filter technique has been chosen for the following considerations: The latitude of each one of the selected emissions is of the order of 10^{-2} Å (at normal ionospheric temperatures). There exists no filter with such resolution. The filters used in the equipment have a half-latitude of 50 Å. Therefore, each filter together with the emission is also pervious by the spectral phone. We used

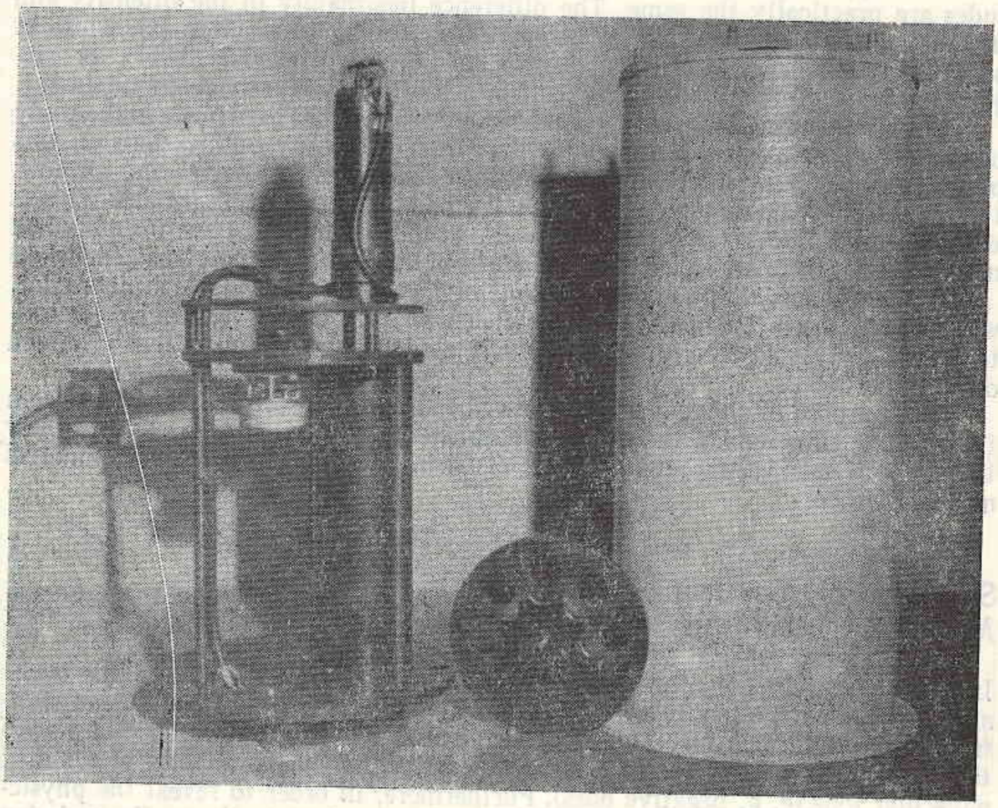

Fig. 1

a second filter in order to isolate the phone, and by that filter we measured the phone close to the emission.

The electrophotometer used for the observations consisted of an optical system (full angle — 10°), a disk with interference filters, and a photoreceiver —

photomultiplier FEU-79. The principle blocks are shown on Fig. 1. Besides the six photofilters, there were two more positions on the disk — one for the measurements of the dark current and another one for mounting the photostandard for the purpose of continuous control over the sensitivity of the equipment. The disk with the photofilters was rotated by a motor provided with reduction gear. More detailed information about the equipment used can be found in [9], and

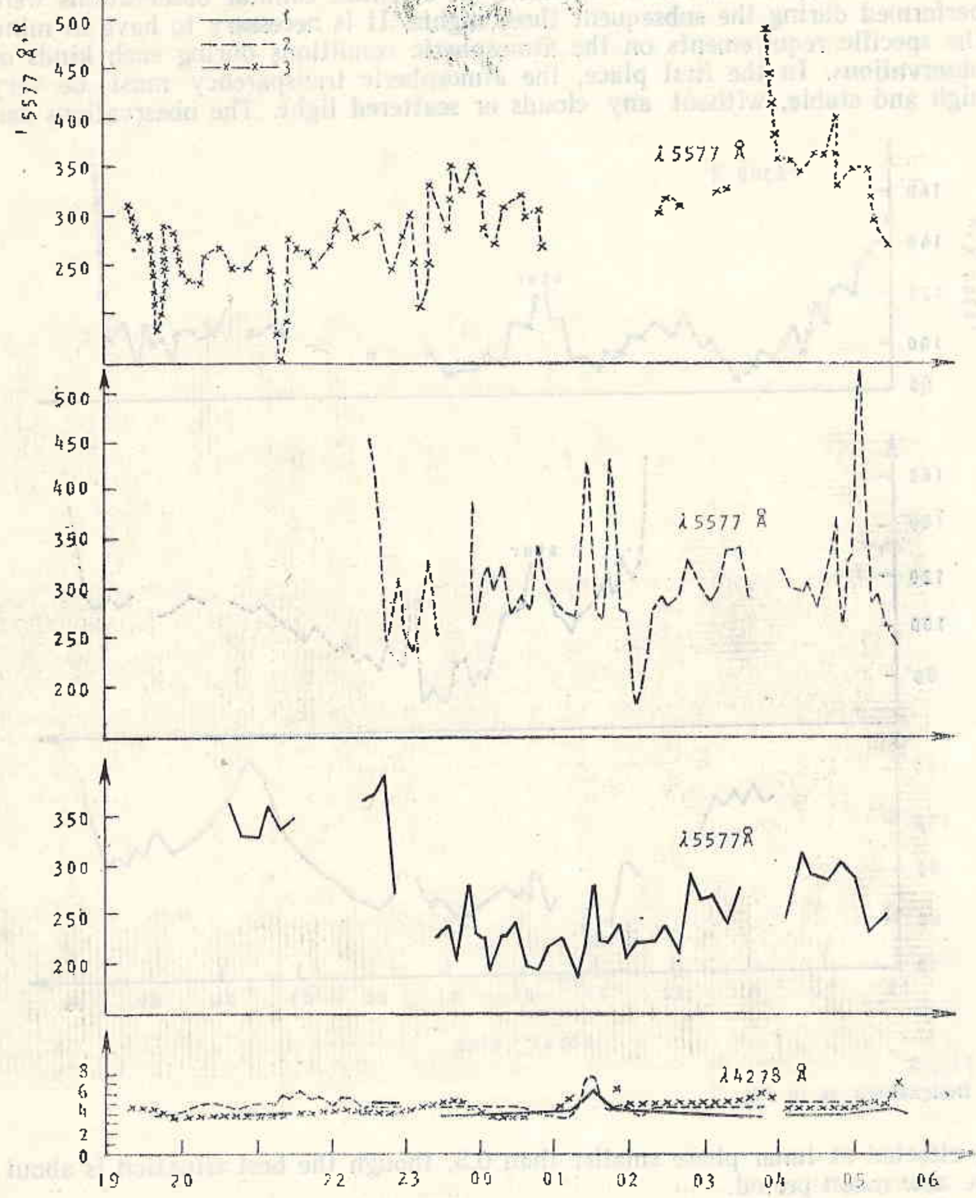

Fig. 2
1 — November 3-4, 1975; *2* — November 4-5, 1975; *3* — November 5-6, 1975, (Havana)

greater details on the electron blocks are to be found in [10]. The technique of information processing is described in [4].

Measurement Results

In Cuba, the first observations on atmospheric emissions were carried out during the nights of November 3-4, 1975, from the area of the Institute of Geophysics and Astronomy of the Cuban Academy of Sciences. Similar observations were performed during the subsequent three nights. It is necessary to have in mind the specific requirements on the atmospheric conditions during such kinds of observations. In the first place, the atmospheric transparency must be very high and stable, without any clouds or scattered light. The obesrvations can

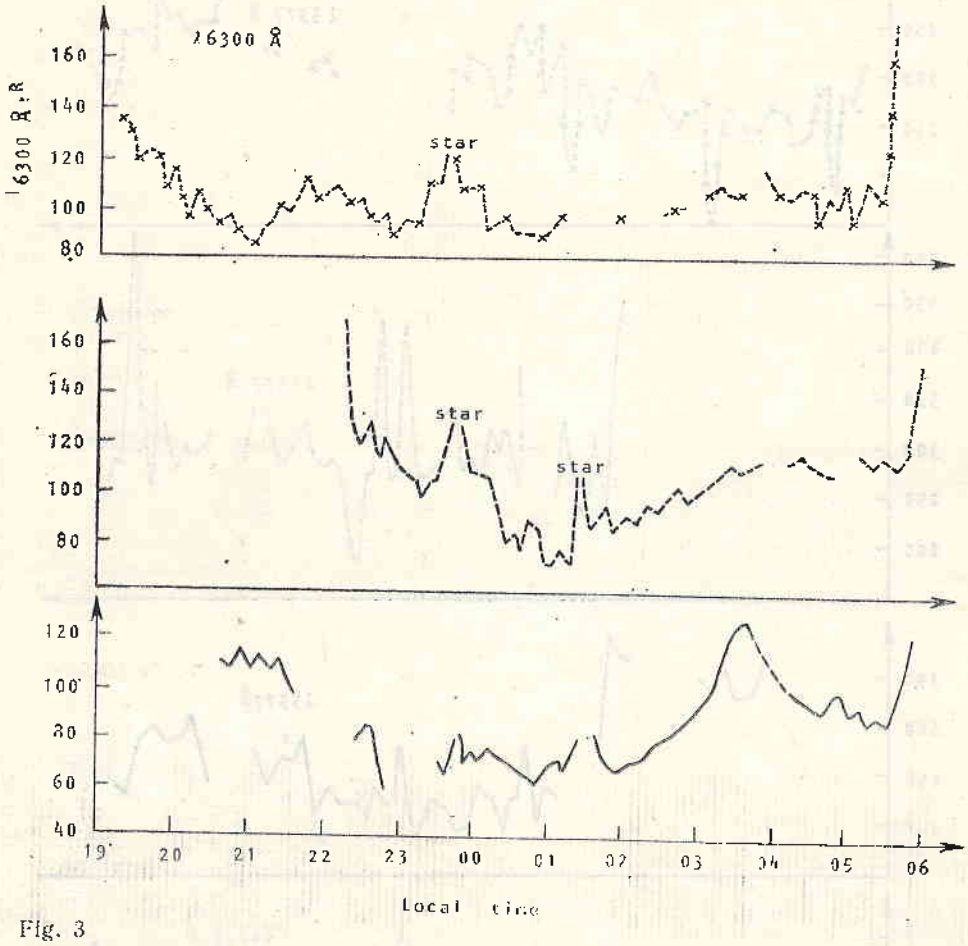

Fig. 3
Designations as in Fig. 2

be effected at lunar phase smaller than 0.5, though the best situation is about the new moon period.

The behaviour of the intensity of the measured atmospheric emissions, depending on the time, is shown in Fig. 2 (green and blue lines) and in Fig. 3 (red line). The threshold sensitivity of the equipment for all three lines is of the order of 4-5 R. The relative error of the measurements is 5 per cent and the temporal resolution is 6-7 min (i. e. two neighbouring values are divided by an interval of 6-7 min for one emission).

The behaviour of the green emission which had been observed for four nights did not differ distinctly from the measurements of this line at midlatitudes — cf. [1, 4, 8, 11]. The emission intensity changed within the range of 190-400 R, which was the normal limit for disturbed conditions. Quick intensity fluctuations were typical here, as in the case of the midlatitudes. This was explained by the fact that the red emission was irradiated in the *E*-region in the range of 80-120 km at a reaction of the following type:

$$O+O+O \rightarrow O_2+O(^1D). \tag{7}$$

This reaction, initially suggested by Chapman, is known as the triple collision. Therefore, oxygen concentration fluctuations (atmospheric density) can strongly influence the intensity of the emission. It is also well known that strong atmospheric turbulence takes place in the region of 100-120 km.

It was interesting to follow the behaviour of the 4270 Å emission during the nights already mentioned (Fig. 2). It can be seen that the intensity of this line changed within a narrow range of 3-4 R. As we have already observed (Section 2), the threshold sensitivity of the equipment was of the order of 4-5 R, and the measurement error was about 5 per cent. Therefore, we can assume with certainty that there was no emission of the 4278 Å line during these nights, i. e. no particle precipitation had taken place. The increase of the order of 7 R recorded at 01:30 was probably due to the pass of a star source through the angle field of the apparatus.

The behaviour of the red line will be examined further on.

Correlation between the Irradiation of the Red Oxygen Emission and Some Parameters of the F-Region

It has been shown by D. Barbier [12] that between $f.F$ and and $h'F$ parameters of the night *F*-region and the irradiation of the red oxygen line there exists a definite relation of the following type:

$$I_{6\,300}=K(f_0F)^2 \exp\left(-\frac{h'F-200}{H}\right)+C, \tag{8}$$

where f_0F is the critical frequency and $h'F$ is the operative height of the *F*-region, while H is the scale height. K and C are two constants determined for each station separately during simultaneous ionospheric and optical observations.

On the basis of a more up-to-date theory of the region, Serafimov and Goshev worked out a new formula in 1972 which is similar to (8), with the empirical constant K of formula (8) now being the following:

$$K=1.24\times 10^4 \cdot R_2[O_2]_{200}, \tag{9}$$

where $K_2=4.10^{-11}$ cm^{3}s^{-1} [3, 6] is the rate constant of exchange reaction (6) and $[O_2]_{200}$ is the molecular oxygen density at 200 km level.

Other publications (e. g. [13, 14]) show the use of the N_e (h) profile for the calculation of the red emission theoretical profile.

Figure 4 shows the behaviour of the λ 6300 Å line intensity (by observations) for the night of November 3-4, 1975, and also the behaviour of f_0F and $h'F$ by observations at the San Jose ionospheric station. Since November 3rd was a magnetically quiet day as regards the solar activity (see Table 1), coefficients K and C

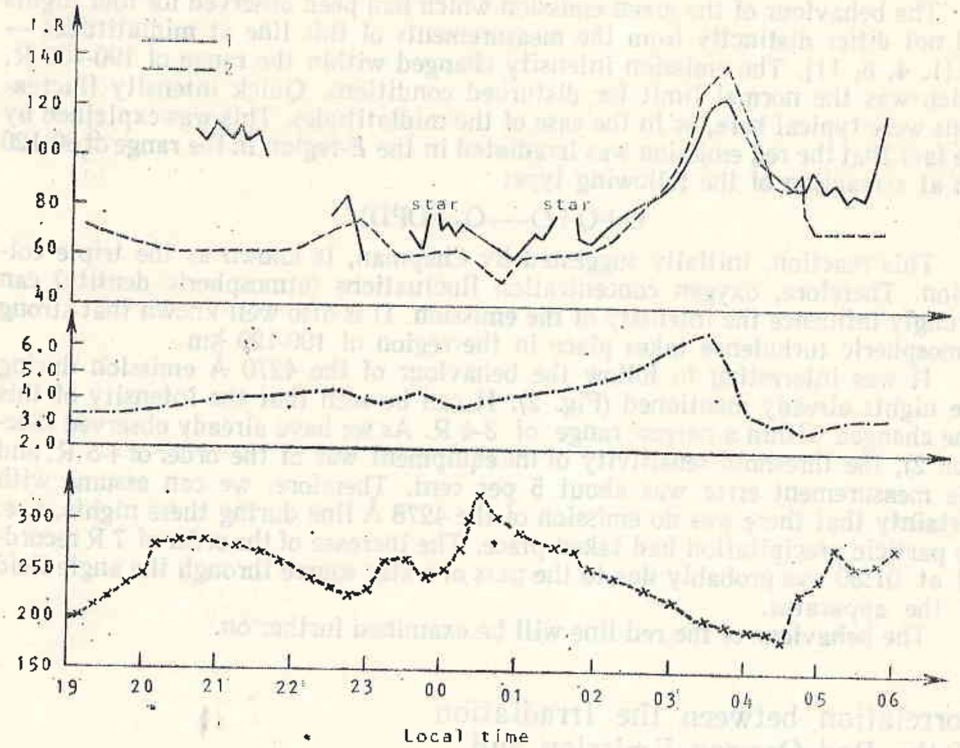

Fig. 4

1 — I_{6300} experimental (November 3-4, 1975, Havana); 2 — I_{6300} theoretical

were calculated, having the following values: $K=1.96$ and $C=60$ R by the correlation function

$$(10) \qquad I_{6300}=f\left[(f_0F)^2 \exp\left(-\frac{h'F-200}{H}\right)\right].$$

After that, using formula (8), the theoretical intensities of the red emission were calculated as shown on Fig. 4.

It should be borne in mind that, on account of the clouds, the apparatus had to be switched off several times (see interval 21:30-22:30; 22:30-22:45; 22:45-23:30). Theoretical-to-experimental data scatter appears during the night and immediately before the morning hours. There was good agreement between theory and practice during the 23:00-04:30 interval. In fact, as shown in [15], formula (8) and the other similar formulas give the rate of the ionospheric recombination. Therefore, Fig. 4 can be interpreted in the following manner: the red emission increase which begins at about 01:00 is due only to the dissociative recombination increase given by formula (3). But it is still difficult to suggest the reasons for that increase.

Before examining the emission behaviour during the other days, we shall examine the solar and geomagnetic activity levels for one period of observation. Data from solar observations were obtained at the Observatory of the Institute of Geophysics and Astronomy of the Cuban Academy of Sciences, with the exception of the radioemission in the range of 10 cm — Boulder. They are given in Table 1.

Table 1

November	1	2	3	4	5	6	7	8	9	10
Radioemission 2 cm	515	516	517	519	523	525	525	526	524	522
Radioemission 4 cm	149	150	151	154	157	159	159	159	156	155
Radioemission 10 cm	72	73	74	77	80	82	82	83	80	80

The radioemission data are given in 10^{-22} w/m³ Hz units.

According to the data obtained, the first days of November were quieter. Over a period of three days — from the 1st to the 3rd November, the radioemission increased from 72 to 74 units. On the 4th day it had already risen to 77, and on the 5th day it rose to 80, remaining constant on the 6th and 7th days. The intensity decreased after the 8th day. The magnetic data show that a magnetic disturbance had set in on the second day and that its maximum appeared about the 4th to the 5th November.

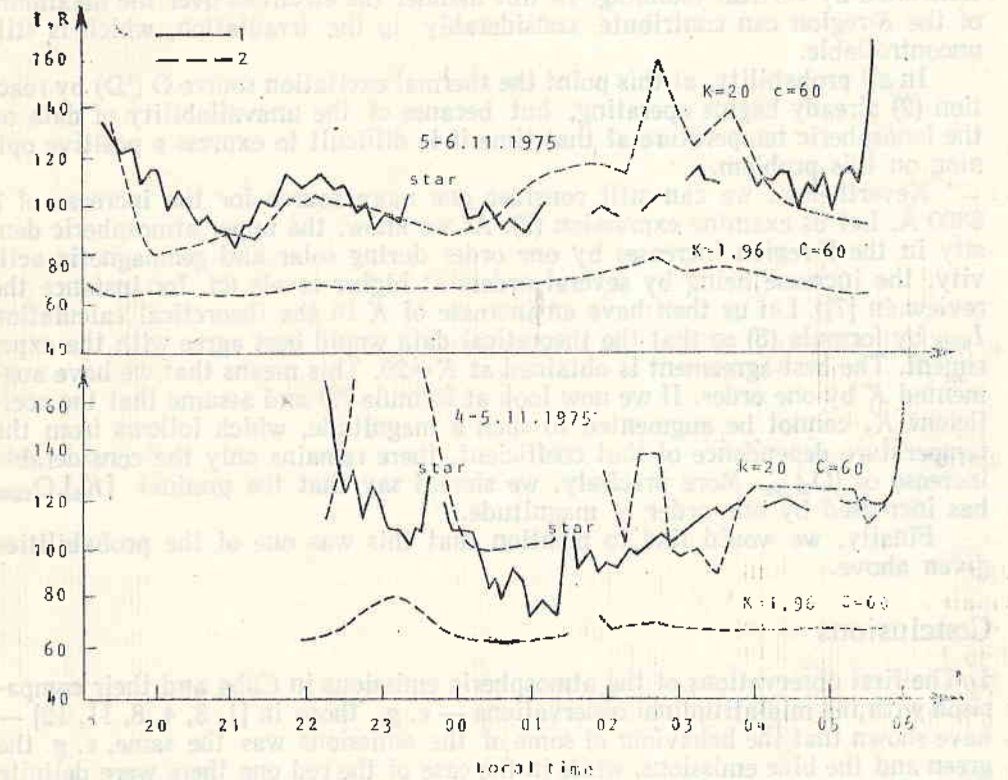

Fig. 5
1 — experimental; *2* — theoretical

Resulting from the increase in solar and geomagnetic activity, there appeared a gradual intensity increase of the red emission, as can be seen in Figs. 4 and 5. Thus the minimum night intensity on the 3rd and 4th November was already of the order of 60 R. On November 4-5 it became of the order of 80 R, and on November 5-6 it rose to more than 90 R.

A bright star source crossed the zenith about 23:45 and 01:30 of the first night, and this resulted in an intensity increase. The disturbance of the peak during the other nights 4-5 minutes earlier than during the first night confirms the fact that it was really a star source.

In addition to the intensity increase, which was probably due to the solar activity increase, we examined yet another important detail. This was the scatter between the experimental and the theoretical data for November 4-5 and 5-6, when in calculating them we used the same constants as for the November 3-4, namely, $K=1.96$ and $C=60$ R. This phenomenon probably has a bearing on the negative ionospheric disturbance during that time — probably the result of the geomagnetic storm. This was immediately to be observed in the night drop of the critical frequencies.

As it is known, one of the suggestions made for explaining such a drop is the redistribution of the electron density in height, which cannot possibly be controlled by vertical sounding. In this manner the electrons over the maximum of the F-region can contribute considerably to the irradiation, which is still uncontrollable.

In all probability, at this point the thermal excitation source O (^{1}D) by reaction (2) already begins operating, but because of the unavailability of data on the ionospheric temperature at that time it is difficult to express a positive opinion on this problem.

Nevertheless, we can still consider one more source for the increase of λ 6300 Å. Let us examine expression (9). As we know, the upper atmospheric density in the F-region increases by one order during solar and geomagnetic activity, the increase being by several orders at higher levels (cf. for instance the review in [7]). Let us then have an increase of K in the theoretical calculation I_{6300} by formula (8) so that the theoretical data would best agree with the experiment. The best agreement is obtained at $K=20$. This means that we have augmented K by one order. If we now look at formula (9) and assume that the coefficient K_2 cannot be augmented to such a magnitude, which follows from the temperature dependence of that coefficient, there remains only the considerable increase of $[O_2]_{200}$. More precisely, we should say that the product $[K_2].O_{2200}$ has increased by one order of magnitude.

Finally, we would like to mention that this was one of the probabilities given above.

Conclusions

1. The first observations of the atmospheric emissions in Cuba and their comparison with the midlatitudinal observations — e. g. those in [1, 3, 4, 8, 11, 12] — have shown that the behaviour of some of the emissions was the same, e. g. the green and the blue emissions, while in the case of the red one there were definite differences.

2. In Cuba, the red emission, which represents the rate of the night recombination process, shows a definite increase after midnight. This results from the dissociative recombinational increase in the F-region. These processes are probably related to the increase of the critical frequencies f_0F after midnight, as described in [17], but their physical mechanism is still unclarified.

3. The first night observations of the 4278 Å emission, though only for three nights during a disturbed period (the maximum K index at that time was $K=4$), showed no remarkable particle precipitation. In any case, if we use the technique given in [18, 19] and keep into consideration the fact that the intensity of λ 4278 Å was close to zero, we are entitled to maintain that the upper boundary of the precipitated electron flux, if such does exist, is below 2×10^{-2} erg/cm² s.

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Первые результаты измерения оптических эмиссий ионосферы, проведенного на Кубе

М. М. Гогошев, С. К. Чапкынов, Х. С. Гонзалес,
Л. Паласио, Ж. Хил

(Резюме)

В введении рассмотрены физические основы существования оптических эмиссий ионосферы. Внимание уделено фотоионизирующим процессам в дневных условиях. Рассмотрены процессы диссоциативной рекомбинации молекулярных ионов в ионосфере.

Целью работы является описание первых результатов измерения оптических эмиссий ионосферы, полученных с помощью болгарской электрофотометрической аппаратуры на территории Республики Куба.

Описана измерительная техника и применяемые при измерениях технические средства; обращено внимание на выбор измеряемых эмиссий.

Приведены результаты измерений и сделаны выводы на основе первых измерений естественных атмосферных оптических эмиссий, проведенных болгаро-кубинским коллективом на Кубе. Дано сопоставление с аналогичными экспериментами, проведенными в средних широтах, и указаны некоторые особенности измерения в низких широтах.