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Abstract

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ALTITUDE DISTRIBUTION OF CHARGED PARTICLES IN THE IONOSPHERE AND THE TRANSITION REGION BETWEEN THE OXYGEN AND HELIUM ION LAYERS ACCORDING TO ION-TRAP EXPERIMENTS ON THE "KOSMOS-2" SATELLITE

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Among the most important results of Soviet ionospheric measurements carried out with geophysical rockets and satellites during the IGY (1–6) is the establishment of previously unknown features of the outer ionosphere (lying above the main ionization maximum): a) the decrease in the concentration of charged particles with increasing altitude in the region close to the maximum in the outer ionosphere occurs much more slowly than its increase with increasing altitude below the main maximum; b) the outer ionosphere up to altitudes $h \sim 1000$ km consists mainly of atomic oxygen ions (O^+).

In 1959-1960 these results were confirmed by American experiments on rockets and satellites (for example, (7,8)). In particular, ion-trap experiments by R. Bourdeau, G. Whipple, and others, carried out on the "Explorer-8" satellite launched in 1960, confirmed that up to altitudes $\sim$ 1000 km there existed a layer consisting mainly of O^+ ions. In addition, they concluded that at greater altitudes (up to $\sim$ 1600 km) there existed a layer also containing a considerable quantity of helium ions He^+ (8).

Experiments carried out by the authors of the present communication with the aid of the "Kosmos-2" satellite, launched on 6 IV 1962, indicate that the above-mentioned features of the outer ionosphere are apparently inherent in it only during a period close to the maximum of solar activity, and change with time.

On this satellite, which had an orbit with perigee $h_{\min} \approx 212$ km, apogee $h_{\max} \approx 1546$ km, and inclination to the equator 49°, a series of experiments was carried out, concerned mainly with the study of the ionosphere. Among other instruments there were 8 flat three-electrode ion traps, arranged on the surface of the satellite, one in each of 8 octants into which space may be divided,

Fig. 1

Figure 1: Fig. 1

so that the angles between the normals to the outer grids of any adjacent traps were $\leq 90^\circ$. The outer grids of these traps had the potential of the satellite body. The satellite also carried spherical three-electrode ion traps, the voltages on whose outer grids varied relative to the satellite body according to a law of bipolar sawtooth pulses; these traps were set away from the surface of the satellite in the same way as had been done on the third Soviet satellite. The principle of operation of the spherical ion traps was described in $^{(9)}$ and more fully in $^{(6)}$. The inner grids in all the traps had a constant negative potential relative to their collectors and were intended for suppressing photoemission and secondary emission of electrons from the collectors.

During a number of revolutions of the satellite around the Earth, the values of the collector currents of all the traps and the voltages on the outer grids of the spherical traps were stored along the entire orbit of the satellite, with playback of the stored information during passage near receiving stations over the territory of the USSR. The storage of this information was carried out at a rate of 12 interrogations per second for each measuring channel, which made it possible to register in sufficient detail the changes in currents in the flat and spherical traps (the duration of the working stroke of the sawtooth volta-

···of the voltage on the shells of the latter was 2 sec). Preliminary results of some of the experiments carried out on the satellite "Cosmos-2" are given below.

Figure 1 shows graphs of measurements of the concentration of positive ions n_i along the satellite orbit during six revolutions of the satellite around the Earth, plotted as functions of height above the Earth. The values of n_i in Fig. 1 were obtained from the data of the system of plane traps as follows. Graphs were constructed of the collector currents I_c, which are the upper envelopes of the field of points corresponding to the values of the collector currents of all eight plane traps. Thus, at a given moment the value I_c corresponded to the current in that one of these eight traps whose normal was closest to the direction of the satellite velocity vector. From the values of I_c, n_i was determined by means of the relation

Fig. 1. Dependence of the concentration of positive ions n_i on height h. a—unilluminated sections of the orbit; b—illuminated sections; v—latitude φ°. Moscow time. The height changes from left to right

$$n_i = \frac{I_c}{\alpha S e V_{\text{sp}}}, \tag{1}$$

where S is the surface area of the outer grid of the plane trap, α is the total transparency of its two grids, e is the electron charge, and V_{sp} is the total

Fig. 2

Figure 2: Fig. 2

velocity of the satellite. Since V_{sp} changes along the orbit slowly and within comparatively small limits, the graph of n_i in Fig. 1 corresponds rather well to the course of the changes in I_c. The possibility of using (1) for an approximate determination of n_i follows from (10,6).

It is seen from Fig. 1 that the decrease of n_i with increasing height above the principal maximum of ionization, for all revolutions of the satellite around the Earth to which the graphs shown refer, has one and the same character—it occurs considerably faster than according to the 1958 data (see the summary graph in (11)), so that the above-mentioned peculiarity of the outer ionosphere is absent. It may be supposed that this is connected with a change in the chemical composition of the ions at the heights under consideration, namely with a lowering of the layer of O^+ ions (caused, for example, by cooling of the upper atmosphere in connection with a decrease in solar activity).

Confirmation of the correctness of such an interpretation can be obtained by analyzing the current-voltage characteristics of the spherical ion trap. K. I. Gringauz and M. Kh. Zelikman (9) were the first to point out the mass-spectrometric capabilities of ion traps on a satellite. We used the data, relating to the region outside the ion shadow created by the satellite, from the spherical trap mounted on a boom 65 cm long. The use···

Using relation (9a), given in [6], one can, from the slope of the upper linear section of the current-voltage characteristic, find the sum of the ratios of the partial ion concentrations to the corresponding mass numbers for each altitude above the Earth. On the same current-voltage characteristics it proved possible to determine the points corresponding to zero potential of the outer grid relative to the neutral plasma, from the onset of appreciable electron currents to the outer grid of the trap. From these points the total concentration of positive ions was readily determined, since at zero potential the effective cross section of the trap, from the standpoint of ion collection, is equal to its geometrical cross section.

Fig. 2. Transition region from atomic oxygen ions to helium ions. (7 IV 1962, 17 hr 04 min –17 hr 08 min Moscow time).
1 –dependence of the reduced mean mass number m'_{cp} on altitude h; 2 –relative content of O^+; 3 –relative content of He^+

Denoting by n_k the partial ion concentrations, by m_k the corresponding mass numbers of the ions, and by m'_{cp} the reduced mean mass number, we have:

$$\frac{n_i}{m'_{\text{cp}}} = \sum_k \frac{n_k}{m_k} = F(h),$$

$$n_i = \sum_k n_k = G(h). \tag{2}$$

From the system of equations (2) we find

$$m'_{\text{cp}} = G(h)/F(h). \tag{3}$$

The quantity m'_{cp} obtained from (3) differs from the ordinarily introduced mean mass number m_{cp}; however, in the case where ions of only one mass are present, $m'_{\text{cp}} = m_k$.

If one idealizes the real chemical composition of the ionosphere and assumes that in the region under consideration ions of two types with different masses dominate, while ions with other masses may be neglected, i.e., assumes a two-component ionic composition ($k = 1, 2$), then from (2) we also obtain the ion concentrations:

$$n_1 = \frac{m_2 F(h) - G(h)}{m_2/m_1 - 1}, \qquad n_2 = G(h) - n_1. \tag{4}$$

As an example, Fig. 2, 1 (according to (3)) shows the dependence $m'_{\text{cp}}(h)$ from the results of measurements carried out on 7 IV 1962 on the unilluminated portion of the orbit shortly after crossing the boundary from the illuminated portion. It follows from this curve that in the altitude interval from ~ 520 km to ~ 610 km, m'_{cp} changed from 16 to 4. Assuming that only He^+ and O^+ ions are present in this transition region ($m_1 = 4, m_2 = 16$), we find n_1 and n_2 from (4). In Fig. 2, 3 the relative content of helium ions $n_1/(n_1 + n_2)$ is presented, and in Fig. 2, 2 that of atomic oxygen ions $n_2/(n_1 + n_2)$, as a function of altitude. Within the framework of the assumptions made, equal contents of He^+ and O^+ occurred at an altitude of ~ 580 km.

At altitudes below 520 km the rectilinear portions of the current-voltage characteristics proved to be very short and did not permit their slope to be determined with sufficient accuracy. Therefore the values of m'_{cp} for $h < 520$ km (see Fig. 2) should be treated with caution. Calculation by formulas (4) under the assumption $m_1 = 1, m_2 = 16$ (H^+, O^+) leads to a transition region lying substantially above 600 km, which is not consistent with the form of the curves $n_i(h)$ in Fig. 1.

The only mass-spectrometric measurements in the outer ionosphere (up to altitudes of ~ 1000 km) during a period close to the maximum of solar activity were the measurements of V. G. Istomin in 1958 on the third Soviet satellite, in which an instrument was used with a range of ion mass numbers from 6 to 48, i.e., He^+ ions could not be recorded (^{5}). In this connection the question arises: did He^+ ions not exist in significant quantities at altitudes of ~ 600 km at that time? Although the results of the experiment themselves (^{5}) cannot answer this question, a joint analysis of them with the results of measurements carried out by means of spherical ion traps on the same satellite makes it possible to assert that at that time there were no significant quantities of He^+ ions at altitudes of 600–800 km. The American experiments carried out in 1960 (^{8}) testify to the same.

Thus there are substantial grounds for considering that, during the measurements on the satellite "Kosmos-2," the structure of the outer ionosphere differed from its structure in the period 1958–1960 in that the transition region between the layer in which O^+ ions dominate and the layer in which He^+ ions dominate was located at considerably lower altitudes, which caused the corresponding changes in the altitude variation of n_i.

The graphs presented in Fig. 1 correspond to a period of magnetic and ionospheric disturbances; disturbances of the same intensity occurred during the flight of the third satellite, for example, 31 V—2 VI 1958, but they did not then cause changes in the character of the altitude distribution of ions in the outer ionosphere. Therefore, the features of the structure of the ionosphere described in the present communication should apparently not be associated with the indicated disturbances.

The lowering of the O^+-ion layer with decreasing solar activity was theoretically predicted in 1960 by Hanson and Ortenburger, who, not yet knowing of the existence in the ionosphere of a layer of He^+ ions, considered the phenomena in what was then assumed to be the transition region between the O^+ and H^+ layers (^{12}), and calculated that this region would descend from an altitude of ~ 1500 km to an altitude of ~ 1000 km.

The results described in the present communication are in satisfactory agreement with the theoretical calculations of Harris and Priester concerning changes in the altitude variation of the mean molecular weight of neutral particles in the upper atmosphere in connection with changes in solar activity (^{13}).

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Note: Figure translations are in progress. See original paper for figures.