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NATURE OF THE POLAR CAP Es - IONIZATION

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Abstract. The unsolved problem of the polar cap flat-type Es-ionization nature is considered by means of reevaluation of previous studies of its main morphological features together with the results of the most recent investigations concerning the formation mechanisms of the thin auroral Es-layers. Such an approach to the problem allowed the authors to make several reasonable conclusions on the issue. The most probable mechanism of the polar cap Es-layers formation is vertical ion drift caused by the electric fields of magnetospheric origin. Gravity and tidal waves can be the decisive factor in the Es-layers formation at invariant latitudes higher than 83,5.

1. Introduction

In recent years the problems of the physical properties of the high-latitude sporadic E-layers have been actively discussed in the scientific literature: [*Whitehead*, 1970], [*Besprozvannaja and Shirochkov*, 1976], [*Besprozvannaja et al.*,1980], [*Nygren et al.*, 1984], [*Olesen et al.*, 1986], [*Huuskonen et al.*, 1988], [*Bristow and Watkins*, 1991], [*Shirochkov et al.*, 1992], [*Kirkwood and von Zahn*, 1991, 1993]. There are strong reasons to believe that the polar cap Es- ionization is a separate geophysical phenomenon with the special features other than auroral E properties. The goal of this paper is to search for probable physical mechanism of formation of the polar cap Es-layers taking into account also the results of detailed research of formation of such layers in the auroral zone performed by several groups of researchers and the specific morphological features of the polar cap Es -layers described in the previous studies [*Besprozvannaja and Shirochkov*, 1976; *Besprozvannaja et al.*, 1980]. It seems that such an approach is the most promising way to find a reasonable answer to the problem of the polar cap Es- ionization nature which is still unclear, mostly due to scarcity of the reliable observational data in the polar cap ionosphere. Almost all available information on the subject is derived from the vertical ionozonde data. Some contribution to the problem was made by the data of the forward scatter radiopaths operated in the Southern polar cap in 1964-1969 [*Baird*, 1968] as well as by the backscatter radar observations in very high geomagnetic latitudes in Arctic in 1962-1964 [*Gerson*,1969]. The main morphological features of the polar cap Es- ionization described in those studies are the following.

1. The dominant class of the polar cap Es- ionization is the thin flat- type Es-layer with very faint blanketing properties [*Besprozvannaja and Shirochkov*, 1976; *Besprozvannaja et al.*, 1980].

2. The most prominent feature of the polar cap Es- ionization is strong dependence of its occurrence probability on the interplanetary magnetic field (IMF) orientation, especially on its azymuthal component (By)- [*Besprozvannaja and Shirochkov*, 1976]

3. There is distinct anticorrelation between the polar cap Es occurrence probablity and the geomagnetic activity level [*Besprozvannaja and Shirochkov*, 1976].

4. Existing intensity of the ion and electron precipitation in the polar caps is too low to produce experimentally observed Es- layers in this area [*Baird*, 1968].

5. There are strong solar cycle variations in the polar cap Es occurrence probability with maximum Es appearance in the years of the highest solar activity [*Shirochkov*, 1977].

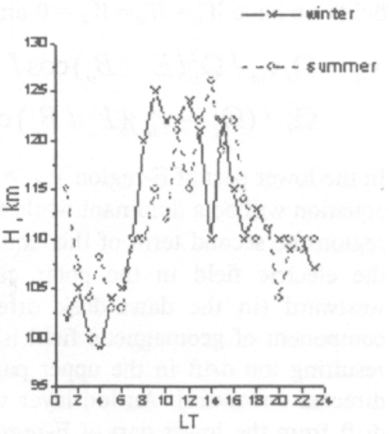

Fig.1. The seasonal variations of the virtual heights of Es-layers at Vostok Station (Antarctica) for 1970 (maximum solar activity).

6. The diurnal variations (LT) of the polar cap Es occurrence probability in the center of the polar cap have a wavelike form with its minimum at the morning hours and maximum at the afternoon hours. At invariant latitudes less than - 83.5 an additional maximum of Es occurrence appears near the midnight in MLT where Es occurrence is proportional to geomagnetic activity [*Gerson*, 1969; *Shirochkov*, 1977]. Most probably this secondary Es maximum which is more pronounced in winter is a result of the auroral oval approach to a point of observation.

7. Diurnal variations of the virtual height of the polar cap Es derived from the vertical ionozonde data have a maximum at noon of LT in all the seasons (Figure 1).

The data from [*Shirochkov*,1977] demonstrated the solar cycle variations of the polar cap Es occurrence probability at Thule (Greenland) (invariant latitude 86.0 N) and at Vostok (Antarctica) (invariant latitude 83.3 S) are shown here in Figure 2 for all the seasons. The data for Thule (upper panel) are given for 1960 (the sunspot number W = 122.3), 1961 (W = 53.9) and 1964 (W = 10.2) while those for Vostok (lower panel) are for 1963 (W = 105.5), 1966 (W = 47.0) and 1965 (W = 15.1). It is evident that the solar cycle variations are more significant at Thule than at Vostok although the geographic latitudes of both stations are very close (77.48 for Thule and 78.45 for Vostok). Additional nighttime maximum of Es at Vostok can be clearly seen. The electron concentration value expressed as foE in the regular E region in the polar cap does not demonstrate any solar cycle variations neither for noon nor for midnight periods. The aforesaid morphological features of the polar cap Es-layers are certainly real since they are derived from the long-term reliable experimental data.Therefore any physical mechanism of the polar cap Es formation must explain these features.

2. Discussion

Remarkable dependence of the Es appearance in the polar caps on the IMF orientation [*Besprozvannaja and Shirochkov*, 1976; *Besprozvannaja et al.*, 1980] is a strong evidence of importance of the ionospheric electric field in formation of the polar cap Es layers. In fact the temporal/ spatial distribution of Es resembles strongly the similar distribution of the electric fields in the polar ionosphere under IMF control [*Friis-Christensen et al.*,1985]. Neither neutral wind in the polar atmosphere nor the metallic ion distribution at the same heights are expected to demonstrate such dependence. Simple theoretical considerations are the following. Vertical component of the ion drift V under influence of the electric field and neutral wind can be expressed as

$$v_{iz} = \Omega_i \nu_{in} / (\Omega_i^2 + \nu_{in}^2) + (E_n / B_o + W_e)\cos I + \Omega_i^2 / (\Omega_i^2 + \nu_{in}^2)(E_e / B_o + W_n \sin I)\cos I + (1 - \cos^2 I\, \Omega_i^2 / \Omega_i^2 + \nu_{in}^2) W_z \qquad (1)$$

where ν_{in} is the ion collision frequency, Ω_i is gyrofrequency of ions, I is inclination of the magnetic field, E_e and E_n are eastward and northward components of the electric field, W_n, W_e and W_z are horizontal (northward and eastward) and vertical components of the neutral wind.

The geomagnetic field B is directed downward in the Northern Hemisphere. Under influence of only electric fields we have $W_n = W_e = W_z = 0$ and correspondingly

$$v_{iz} = \Omega_i \nu_{in} / \Omega_i^2 (E_n / B_o)\cos I + \Omega_i^2 / (\Omega_i^2 + \nu_{in}^2)(E_e / B_o)\cos I \qquad (2)$$

In the lower part of E-region $\nu_{in} > \Omega_i$ so the first term of equation will be a dominant while for the upper part of E-region the second term of this equation will dominate. If the electric field in the polar cap is oriented mainly westward (in the dawn-dusk direction) and horizontal component of geomagnetic field is directed poleward the resulting ion drift in the upper part of E- region will be directed downward. An ion layer will be produced if ion drift from the lower part of E-region is directed upward. Such ion drift is possible if meridional component of the electric field will be oriented poleward on the nightside what in its turn is possible under western magnetic deviation. So the position of the observation point is essential for Es-layer formation in the polar cap. As it is known the electric field distribution at the high- latitudes is controlled by the IMF orientation. *Potemra et al.*[1984] have shown that westward component of electric field depends on the By-orientation; it is observed at the afternoon hours in the Northern hemisphere when By>0, and in the Southern hemisphere when By<O, which corresponds exactly to appearance of the polar cap Es layers [*Besprozvannaja et al.*,1980]. It is worth noting that the both ion drift velocity and direction depend on geomagnetic inclination I. It means that one could not expect

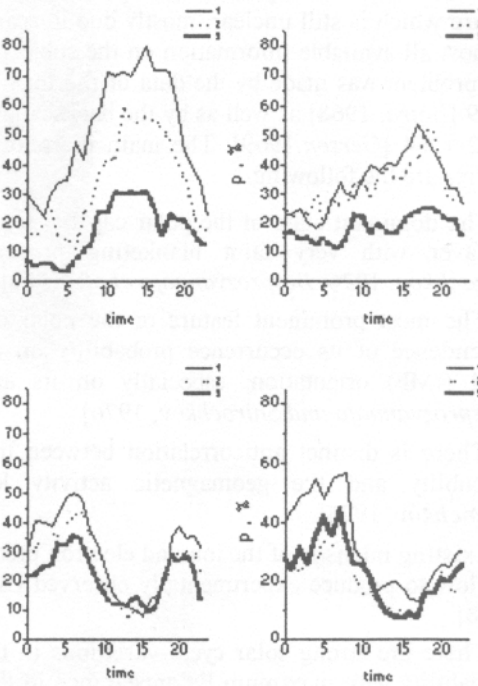

Fig.2. The solar cycle variations of the Es occurrence probability for Thule (upper panel) and Vostok (lower panel) for summer (left part of each panel) and winter (right part). The years for Thule are: 1 (1960, W=122,3); 2 (1961,W=53,9); and 3 (1964,W=10,2) while for Vostok 1 they are (1969, W=105,5); 2 (1966, W=47,0) and 3 (1965, W=15,1). The data are given in local time.

any appearance of Es at geomagnetic pole where $\cos I = 0$. Most probably other factors such as the neutral winds together with tidal and gravity waves are responsible for Es formation in the near pole region. Some evidence of this phenomenon can be found in our Figure 2, where the more distinctive solar cycle variations of the Es appearance are seen at Thule which is located closer to geomagnetic pole than Vostok, where these variations are much smaller. As for an altitude of Es-layers it depends on both ion gyrofrequency and ion collision frequency. Since gyrofrequency is almost constant at the heights of Es locations the ion collision frequency remains as the main factor. It can be expressed as [*Hanson*, 1969]:

$$\nu_{in} = 2.6 \cdot 10^{-9}(N_n + N_i)M^{-1/2} \tag{3}$$

where N_n is concentration of neutral gas, N_i is ion concentration, M is molecular weight of the neutral gas components. Since the parameters of the neutral atmosphere depend on both solar and geomagnetic activities level one can expect different conditions for the Es formation. According to [*Hanson*,1969] the daytime ion collision frequency values at 150 km exceed the correspondent nighttime values for 50 %. in the epoch of maximum solar activity. Our data in Figure 1 demonstrate this dependence nicely. Any evaluation of the properties of the Es-layers must be made by analyzing the continuity equation

$$\partial N / \partial t = q - \alpha_{eff} N_i^2 - div(NV) \tag{4}$$

where q is ion production rate, α_{eff} is effective recombination coefficient, V is the velocity of ion drift. *Rishbeth and Garriott* [1969] have shown that in the ionosphere E- region under condition of the strong vertical plasma drift and for $\partial N_i / \partial z = 0$ ionization does not depend on the production rate and can be expressed as

$$N_i^{max} = \partial V_i / \partial z / \alpha_{eff} \tag{5}$$

Furthermore, a layer reaches equlibrium condition in the period proportional to $\tau = 1 / \partial V_i / \partial z$, what means that for typical parameters of the E-layer it is equal to several minutes. These equations can be used for checking the real properties of the E-layers observed in the different experiments. First of all probable dependence of N_i^{max} on α_{eff} must reveal itself in the seasonal and solar cycle Es variations. If one assumes that the dominant ions in the Es-layer are ion NO^+ and ion O_2^+ it would mean that an efficient recombination coefficient can be expressed as

$$\alpha_{eff} = 2.1 \times 10^{-7} (300/T_e)^{0.85} (1+0.38 (300/T_e)^{0.3}) \tag{6}$$

Any increase in T_e must lead to corresponding increase in N_e in the E-layer and its highest probability of occurence. The same can be said about the seasonal variations of Es layer. The data in our Fig.2 demonstrate such dependence excellently. Not much can be said about the role of metallic ions in the polar cap Es formation if to take into account that experimental data on their content in the polar cap E- region are very few. The results of some rocket measurements performed at the Heiss Island (invariant latitude 74,9 degrees) in different years by Russian scientists are summarized in [*Pochunkov and Tulinov*, personal communication, 1985]. Their data show that the metal ions are a very rare component of the polar lower ionosphere. The only case of their appearance (from more than 20 launches) was registered at the nighttime hours when the heights of Es are the lowest (see our Figure 1). It is very unrealistic to imagine that the metal ion content in the polar ionosphere depends on the interplanetary magnetic field orientation or on the the geomagnetic activity level. So it is possible to conclude that the metal ions play a minor role in the polar cap Es-formation especially at the daytime when the Es- heights are comparatively high (see our Figure1). Most probably the mechanism of the polar cap Es formation is closely connected with the electric fields of magnetospheric origin which depend strongly on the IMF orientation and consequently, geomagnetic activity level. The preferable orientations of the electric fields in this case are northward and westward. Consequently the region of change of this electric fields orientation can be considered as the frontier of the polar cap Es domain, and the polar cap Es appearance area can be a good indicator of the place of reversal of the electric fields orientation at the high latitudes. The neutral atmosphere processes connected with the gravity and tidal waves seem to play decisive role in the Es-formation in the area located near the geomagnetic poles where geomagnetic inclination is almost 90 degrees.

3. Conclusions

1. Validity of the existing physical mechanisms of low altitude thin Es-layers formation was explored in the case of the polar cap Es-ionization.

2. The requirement was set that any proposed mechanism of the polar cap Es-layer formation can to explain the main morphological properties of these layers, found earlier.

3. It was demonstrated that the electric fields of magnetospheric origin play a major role in the polar cap Es-ionization formation.

4. It seems that metal ions can not be considered as a vital part of the polar cap Es-ionization.
5. The properties of the nearpole Es- layers can be explained as the result of the gravity and tidal waves action together with the neutral winds.
6. All these conclusions must be considered as the preliminary ones, and the experimental campaign in the polar cap area similar to the METAL campaign of 1991 is badly needed in order to clarify many problems connected with the polar cap Es-layers.

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