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GENERAL OVERVIEW OF THE SOLAR ACTIVITY EFFECTS ON THE LOWER IONOSPHERE

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Abstract

Solar activity influences the ionospheric D - region. That influence manifests both in the form of various solar induced disturbances and in the form of the D - region dependence on solar activity parameters (UV-flux, interplanetary magnetic field, solar wind ets) in quiet conditions. Relation between solar activity and meteorological control of the D region behaviour is considered in detail and examples of strong variations of aeronomical parameters due to solar or meteorological events are given.

The question of solar activity (SA) influence on the ionospheric D-region is not as simple as it might look at the first approach. The matter is, that D-region as well as the whole ionosphere occurs as a result of the ionization process in the terrestrial neutral atmosphere which in its turn is completely controlled by the sun. Thus, considering solar activity influence on the D-region one has to distinguish direct effects, when this influence comes through variations of ionizing agents (electromagnetic, or corpuscular), and indirect ones, when solar activity alters the state of neutral medium, which leads to corresponding changes in the state of the ionized component.

The direct effects are more obvious and easy to understand. They come from the fact that the electron concentration $[e]$ which we consider as the most important characteristic of the D-region is defined (in quazi-equilibrium conditions) by

$$q = [e] \cdot \alpha_{eff} \qquad (I)$$

q being the ionization rate and α_{eff} - effective recombination coefficient. All the direct effects of SA on the D-region are contained in q even though α_{eff} may vary and be dependent on SA through indirect effects.

Thus, it is worth briefly considering the ionization sources in the D-region and discussing their variations with SA. It is well known that most part of the D-region ionization is due to solar Layman-α emission interacting with nitric oxide molecules. Layman is considered as a stable enough emission. Its variations during the whole solar cycle lie between $3 \cdot 10^{11}$ and $6 \cdot 10^{11}$ photons cm^{-2} s^{-1} (SIMON, 1982). According to review (NUSINOV, 1987) various authors accept for Lα - variations from minimum to maximum SA values of 30-100%. These variations are much smaller, than uncertainities (and probably - variations)of NO-concentrations at the D-region heights. Thus, one should not expect well pronounced variations of the D-region behaviour with SA due to Ly-α variations. The other sources of the D-region ionization are X-rays ($\lambda \leq 3.0$ nm), galactic cosmic rays and solar emission with λ = I02.7-III.8 nm (the latter ionizing only excited O_2 ($^1\Delta_g$) molecules). Variations of I02.7-III.8 nm emission do not essentially exceed that of Ly-α (see Table I) so we hardly have here a source of strong D-region variations during SA-sycle. Variations of the galactic cosmic rays with solar activity are well known. Ionization rate q due to cosmic rays in the D-region during solar minimum is nearly twice that during solar maximum.

Table I

Amplitude of maximum to minimum SA (M/m) variations of various ionization sources

Source	Ly-α	I02.7-III.8nm	X-rays	Cosmic rays
M/m	I.3-2	2-2.5	5-I0	0.6
Ref.	(NUSINOV,I987)	(HINTEREGGER, I98I)	(BANKS and KOCKARTS, I974)	(BRASSEUR and SOLOMON,I984)

The most changeable ionizing agent in the D-region is X-rays. Variations of its intensity during solar cycle depends on wavelength and generally are strong enough. The values of X-ray flux for λ = 4.I - 3.I nm and levels of SA (very quiet, quiet, moderate, high) according to BANKS and KOCKARTS (I973) are 7.5 $I0^6$, I.5 $I0^7$, 3.0 $I0^7$ and 4.5 $I0^7$ $cm^{-1}s^{-1}$.

Fig. I shows q - values in the D-region due to various ionization sources and their possible variations from minumum SA(m) to maximum SA(M). It is seen that even during high SA the imput of X-rays in the ionization rate q is small in the most part of the D-region. That means that we should hardly expect regular changes of the D-region ionization rate during SA cycle stronger than variations of Ly-α intensity.

Looking at formula (I) we see that the latter means that we should expect $[e]$ variations with the amplitude of I.I5-I.4 if there is a quadratic recombination law (α_{eff} is constant at fixed height) and of I.3-2 if there is a linear law (α_{eff} vary nearly as $[e]^{-1}$).

In fact that is what we see in due experimental data - regular variations of the D-region electron concentration in the solar cycle are rather weak and much less, than that due to various disturbances. To illustrate that, we use the figure showing $[e]$ variation with solar zenith angle χ for summer conditions (DANILOV et al., I982) and mark at each point the value of $F_{I0.7}$ - flux for the day of the experiment (see Fig.2). As one can see from that Figure there seems to be no pronounced dependence on $F_{I0.7}$ - all the experimental points lie on the same curve representing $[e]$ - dependence on χ .

Quite different picture we have for various events, manifesting SA. There we have very strong variations of ionization rate q with consequent changes of all the D-region parameters. Table 2 shows variations of q due to x-rays ionization during solar flares of various intensity (prominent, strong, moderate) according to MITRA (I974).

Table 2.

Ionization rates in the D-region due to solar flares according to MITRA (1974)

h, km	q cm^{-3} s^{-1}		
	Prominent	Strong	Moderate
60	2.10^{1}	1.5	$1.2\ 10^{-1}$
65	6.10^{1}	4	4.10^{-1}
70	$1.5\ 10^{2}$	$1.2\ 10^{1}$	1
75	$5\ 10^{2}$	$4\ 10^{1}$	3.5
80	$1.5\ 10^{3}$	10^{2}	10^{1}
85	$3\ 10^{3}$	$2.5\ 10^{2}$	$2.5\ 10^{1}$

Fig.3 presents variations of q-values during SPE events (SWIDER, 1979). Comparing both sets of q with Fig.1 one can see, that the ionization rates due to X-rays and energetic particles in disturbed conditions are several magnitude higher than in quiet conditions. It is worth emphasizing that during very strong SPE or REP (relative electron precipitation) events strong ionization may take place even at altitudes much lower than normal D-region down to 30-40 km (see BRASSEUR and SOLOMON, 1984). An example of that also give curves 5-7 in Fig.3.

Strong variations of q in the D-region should inevitably lead to essential changes not only of $[e]$ but of the whole recombination cycle as well, including α_{eff}, rate of clustered ions formation B, ion composition parameter f^{+}, negative ions parameter λ and so on. For SPE events we have data on the effective recombination coefficient which show that there in fact is a variation (decrease of α_{eff}) during the events. Fig.4 (DANILOV and SIMONOV, 1981) show values of α_{eff} for summer (1972) and winter (1969) SPE-events. It is well seen that α_{eff} in disturbed conditions ($[e] \geq 10^{4}$ cm^{-3}) is much lower (especially for winter SPE) than for quiet conditions ($[e] \leq 10^{3}$ cm^{-3}). Theory of the ionization cycle in the upper D-region (DANILOV, 1986) gives a clear explanation to that fact - the decrease of α_{eff} is due to decrease of the ion composition parameter f^{+} ($f^{+} = [clus^{+}]/[NO^{+}, O_2^{+}]$). That effect has been measured for 1969 SPE - event (NARCISI, 1972).

Table 3

Values of the ion composition parameter f^{+} for quiet winter conditions and for November, 1969 SPE

	Day 80 km	Day 85 km	Night 80 km	Night 85 km
Winter (average)	2.0	$5\cdot10^{-1}$	$2\cdot10^{1}$	$> 10^{-1}$
SPE-1969	$9\cdot10^{-3}$	$1.9\cdot10^{-4}$	$1.6\cdot10^{-2}$	$5.9\cdot10^{-4}$

The f^{+}- parameter in its own turn decreases because of the reducing of the effectiveness of clustered ion formation B. In the SPE conditions the primary ions produced by the process of ionization became O_2^+ instead of NO^+ in quite conditions and that leads to substatution of B (No^+) by B(O_2^+), the latter at fixed height being lower, than the former.

In the lower part of the D-region where there is a saturation of clustered ions ($f^+ >> 10$) and variations of f^+ - parameter does not influence α_{eff}, the latter during disturbances of SPE-type still changes, but due to decrease of the negative ion parameter λ, because

$$\alpha_{eff} = (1 + \lambda)(\alpha^* + \lambda \alpha_i) \qquad (2)$$

where α^* and α_i - averaged constants of dissotiative recombination and mutual recombination process correspondingly.

Principally the same picture should take place during sudden ionospheric disturbances SID, following solar flares. During SID we observe strong enchancement of $[e]$ and reducing of α_{eff} (MITRA 1974) but there is no ion composition measurements to check the effects of f^+ decrease.

Weaker, but nevertheless much pronounced changes of the D-region parameters do take place during other events, produced by the energetic particle fluxes (Auroral Absorption AA, REP). In all those cases we have increase in the electron concentration due to enhanced q-values and decreased α_{eff}.

One more comment should be made concerning Fig.4. There is a well pronounced difference between α_{eff} - values for summer and winter SPE. This difference reflects the fact that there is a strong seasonal variation of α_{eff} (see DANILOV and SIMONOV, 1981) due to seasonal variations of the ion composition, produced by meteorological processes (DANILOV, 1986). That means that effect of solar event (for example SPE) is modulated by the meteorological influence. In our particular case that means that the same SPA-proton fluxes (the same q) produce much stronger disturbances of the electron concentration in winter than in summer.

Summarising the above said one may state that there are two types of influence on the ionospheric D-region - direct solar and meteorological. If we compare the magnetude of the effects due to SA and meteorological control we wll find (see Table 4) that regular variations of the meteorological origin are much stronger than that due to SA. For spontaneous disturbances the picture is quite opposite - the amplitudes of variations for the principal parameters are higher for SA-produced events.

Above we have already mentioned the effect of α_{eff} decrease during SPE-events. That decrease strongly depends on the season, and that is a good example of the meteorological control filtering the effects of SA. In fact it happens rather often, because the reaction of the D-region to the external disturbance (in the form of X-rays or corpuscules) depends upon the internal state of the D-region (ion composition, λ - ratio, effective recombination coefficient), determined mainly by the neutral atmosphere and so controlled by the meteorological processes.

Table 4
Amplitudes of SA and meteorological effects in the upper D-region

	[e]	α_{eff}	f^+
		Regular	
SA	< 50%	< 50%	< 50%
Seasonal	2	2-3	5-10
		Spontaneous	
SPE	$> 10^2$	≈ 10	10^2-10^3
WA	$\approx 10^2$	3-4	≈ 30

A good example of that statement provides Fig.5 (DANILOV et al., 1983), demonstrating seasonal variation of the sudden phase anomaly (SPA) effects in VLF. Fig.5 shows that the reaction of the D-region on solar flares is different for summer and winter, which manifests the meteorological control of the pure effect of SA.

There is the other side of the medal. Having some ways to influence the middle atmosphere dynamics and/or thermodynamics by SA without direct effect on the D-region we have indirect SA influence on the latter through the alteration of the meteorological situation. The most obvious example is variation of solar UV-emission in 120-200 nm interval. This emission is not able to change q-values in the D-region, but influences the O_2 dissotiation and so by the formation of the ozone should alter dynamical picture in the whole middle atmosphere. The latter, as we understand now, is strictly connected with many aspects of structure and photochemistry (including conditions for propagation of internal gravity ways) and so will influence the D-region through minor constituents, temperature dependence of reaction rates, turbulence ets. That is what we call indirect influence of SA on the lower ionosphere.

That kind of influence is probably the one which provides observed connection of the D-region behaviour with such manifestations of SA as solar wind (see LASTOVICKA 1988) and geomagnetic activity. If we put aside events with strong enough electron precepitation we will find that there is no correlation with geomagnetic activity and no or rather weak correlation with solar activity (LASTOVICKA and SKOBODA, 1987). The latter means that (since we cannot imagine negative influence of SA on the D-region) the direct positive effect of SA is compensated by the indirect one through SA influence on the middle atmosphere as a whole.

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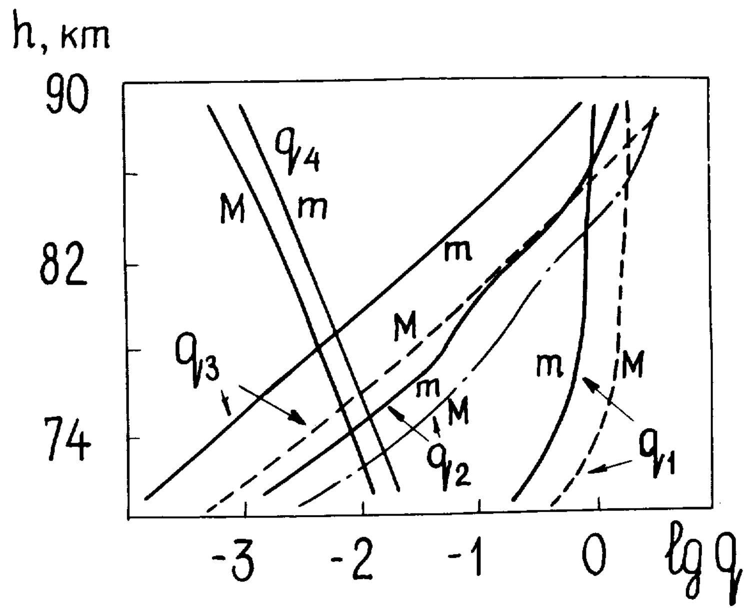

Fig.I. Ionization rates in the D-region for maximum (M) and minimum (m) SA due to various sources: Ly-plus NO - q_I; λ =III.8 - I02.7 nm plus O_2 ($^1\Delta_g$) - q_2; x rays - q_3; cosmic rays - q_4.

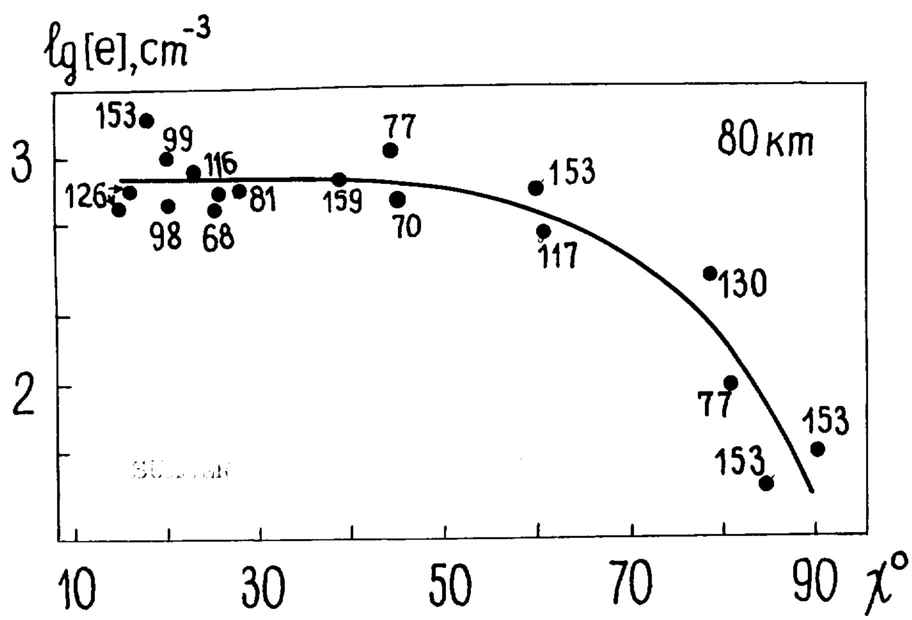

Fig.2. Electron concentration measured on rockets in summer at various solar zenith angles χ . Numbers at the points show solar I0.7 - cm flux at the day of the flight.

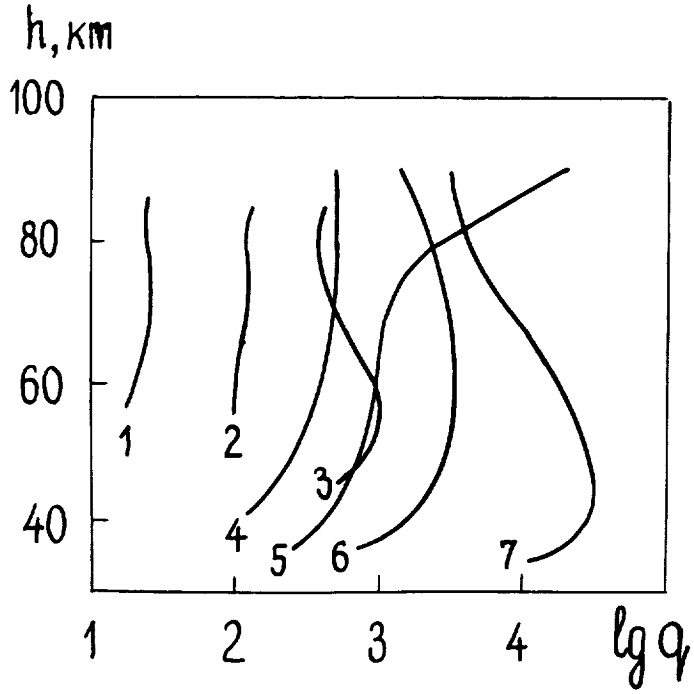

Fig.3. Ionization rates in the D-region during SPE-events according to Swider (1979) (1-3 Nov.1969 event, 4-7 Aug. 1972 event)

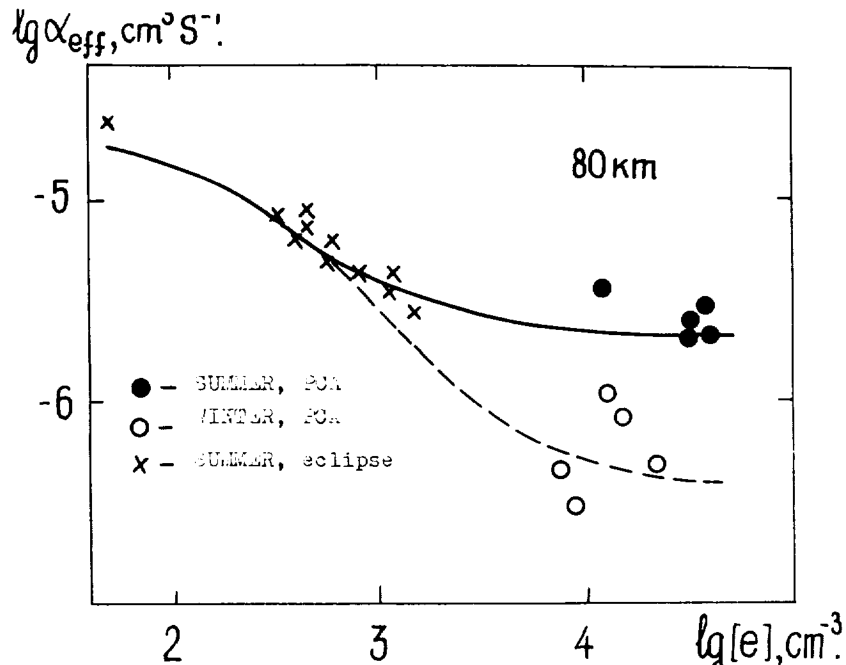

Fig.4. Variations of the effective recombination coefficient α_{eff} in summer (solid line) and winter (broken line) conditions (Danilov and Simonov, 1981).

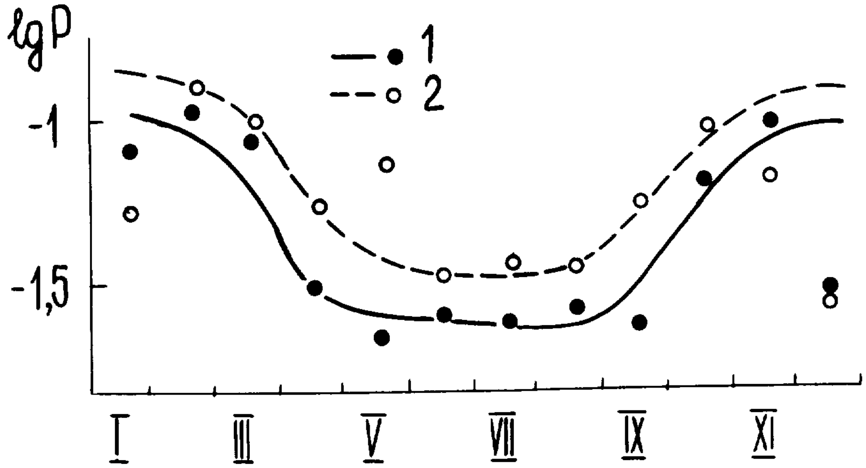

Fig.5. Seasonal variation of P (fraction of illuminated time when SPA effects were observed) in 1979 according to Danilov et al. (1983). (1 - Leningrad, 2 - Kühlungsborn).

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