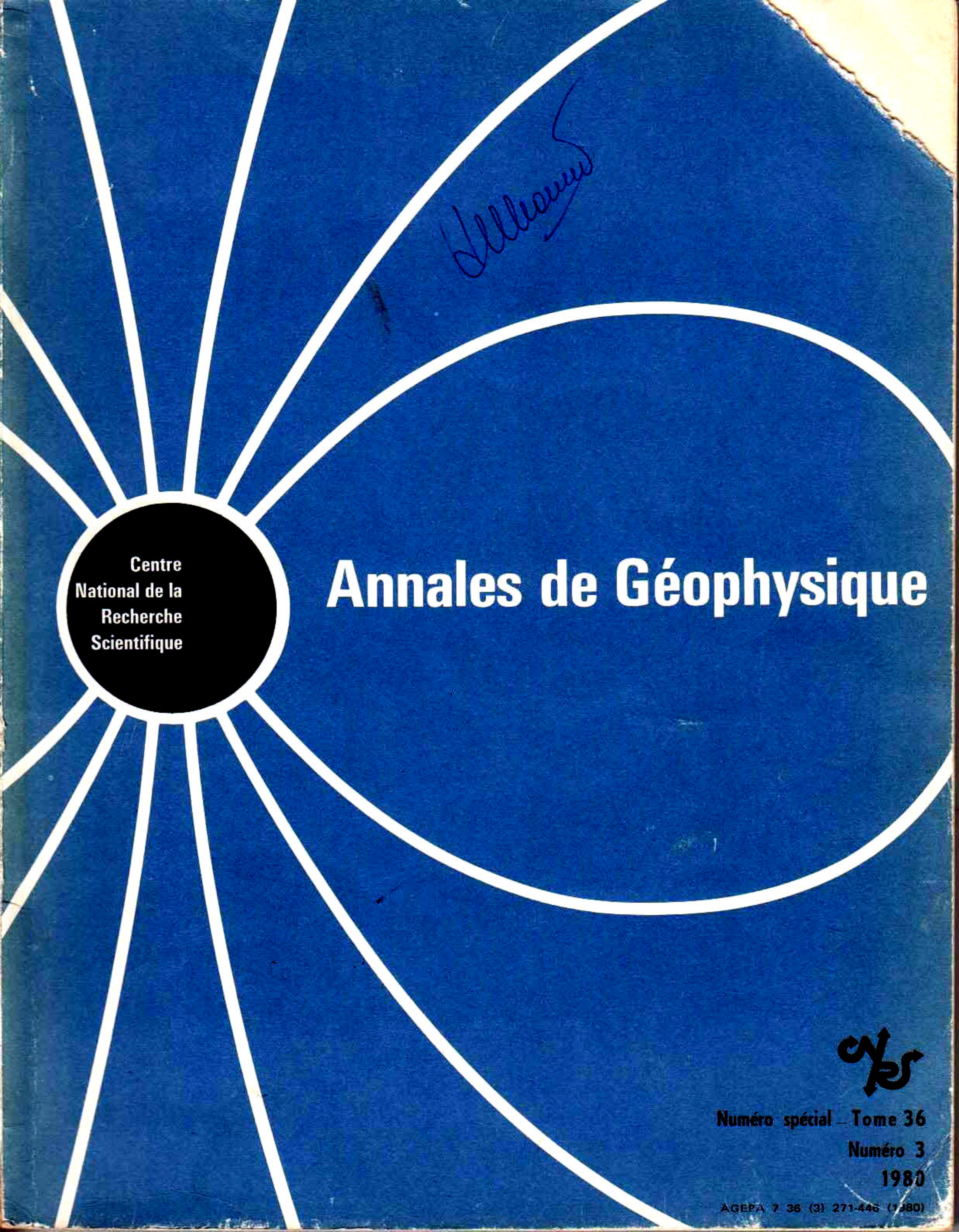

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NUMÉRO CONSACRÉ AUX RÉSULTATS DES EXPÉRIENCES ACTIVES FRANCO-SOVIÉTIQUES ARAKS

SPECIAL ISSUE ON THE RESULTS OF THE ACTIVE FRENCH-SOVIET ARAKS EXPERIMENTS

Edité par **Henri REME**
C.E.S.R. Toulouse

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The study of electron fluxes with energy $\leqslant$ 3 keV in the Araks experiment of January 26, 1975

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ABSTRACT. – *The results of electron fluxes study by means of Retarding Potential Analyzers (R.P.A.) during the Araks rocket flight of January 26, 1975 are given. It is shown that when electron current pulses with duration $\tau = 2.56$ sec approximately along geomagnetic field were injected:*

1) Rocket potential ϕ never exceeded ~ 200 volts,

2) At altitudes $\gtrsim$ 130 km the electron fluxes with energies $E > e\phi$ (up to 3000 eV and more) were observed. Intense flux time fluctuations of these electrons were revealed.

RESUME. – *Les résultats de l'étude des flux d'électrons au moyen des analyseurs à potentiel retardateur (R.P.A.) pendant le vol Araks du 26 janvier 1975 sont présentés. On montre que quand étaient injectées les impulsions du courant d'électrons avec une durée de $\tau = 2{,}56$ sec approximativement le long du champ géomagnétique :*

1) Le potentiel de la fusée ϕ n'excédait jamais 200 volts,

2) Aux altitudes de $\gtrsim$ 130 km les flux d'électrons avec des énergies $E > e\phi$ (jusqu'à 3 000 eV et plus) étaient observés. Des fluctuations importantes des flux de ces électrons en fonction du temps ont été mises en évidence.

1. Introduction

In the French Soviet experiment Araks on board of 2 French Eridan rockets launched in January-February of 1975 from Kerguelen in the Indian ocean there were installed Soviet electron accelerators (Sagdeev and Zhulin, 1975 ; Cambou *et al.*, 1978). The scientific payload of these rockets included among the instruments the retarding potential analyzers of electrons (RPA), described in details in Gringauz and Shutte (1976 a) ; Gringauz *et al.* (1978).

The purpose of these RPA instruments was the study of the electron fluxes on the rocket surface from the surrounding space during the electron injector operation.

It should be mentioned that the characteristics of electron fluxes coming to the rocket during the injection pulses were the main source of information on the rocket electrical potential relative to the environment in the great majority of the rocket experiments with the electron injectors. For this purpose measurements with Langmuir probes in the experiment of Israelson and Winckler (1979) and with the electron RPA (Hess *et al.*, 1971 ; Hendrickson *et al.*, 1971 ; Mc Entire *et al.*, 1974 ; Winckler *et al.*, 1975 ; O. Neil *et al.*, 1978 a ; 1978 b) were used. However in the mentioned experiments with RPA the duration of one cycle of retarding voltage corresponded to several pulses of injection and this did not allow the analysis of the dynamics of electron fluxes coming to the rocket and the change of the rocket potential during one injection pulse. The measurements described below made it possible to obtain several retardation curves (i.e. to determine the parameters of electron fluxes several times) during one long injection pulse.

The purpose of this paper is to describe and to discuss the data obtained by means of the electron RPA during the first flight of the experiments.

2. Brief description of experiment

Two identical electron RPA with the normals at 90° to each other and also to the rocket, and injection axis (see Fig. 1a), were mounted.

The analyzer was the cylindrical flat parallel device consisting of the collector and the grid system (Gringauz *et al.*, 1978).

The period of the variation of the analyzing voltage was 0.64 sec and was synchronized with the injector operation (the time of increase of sawtooth voltage from the minimum to the maximum value was 0.56 sec and the decrease time 0.12 sec).

The recording of collector currents and analyzing voltages was made every 30 msec. The retarding voltage changed according to the sawtooth law and varied in one analyzer from 9 V to 300 V and in the other from 90 V to 3 000 V (that excluded the recording of non-accelerated ionospheric electrons). The range of analyzing voltages was divided into 18 intervals in such a way that the voltage steps in the device with $V_{R\,\max} \sim 300$ V varied from 3 V to 20 V (and from 30 V to 200 V in the device with $V_{R\,\max} \sim 3000$ V). The dynamic range of the measured collector currents was 10^{-10} A $\div$ 10^{-6} A ; the set-up time did not exceed 2 10^{-4} sec ; the maximum current density measured by the analyzer was about 2 10^{-7} A/cm^2. If it is assumed that the rocket electric charge obtained during the electron injection is fully compensated by the electron fluxes coming uniformly to the payload from the environment the neutralizing current density should be about 2.5 10^{-5} A/cm^2 (the rocket total surface is about 2 10^4 cm^2). It means that the maximum current measured by the analyzer is almost two orders of magnitude lower than the expected neutralization current.

It has been assumed that the results of the measurements of retardation curves will make it possible to determine the value of the rocket potential to the environment on the basis of the following idealized model (which is too oversimplified as it has become clear after the experiment).

Every instant, only electrons with energies exceeding eV$_R$ (V_R : retarding potential) could get to the collector. During the accelerator operation the rocket can acquire the positive potential which creates the negative space charge around it. If the number of electron collisions inside this space charge region is negligible the cold ionospheric electron should acquire the energy $E = e\phi$ on the input of the analyzers. Then for the retarding potential $|V_R| \leqslant \phi$ the collector current should rise sharply to the $I_{\max}$ value (depending on the density of plasma surrounding the rocket and the ϕ value). The recording of the analyzer current should occur till the condition $|V_R| > \phi$ is realized (see the dependence $\ln I = f(V_R)$ in Fig. 1b).

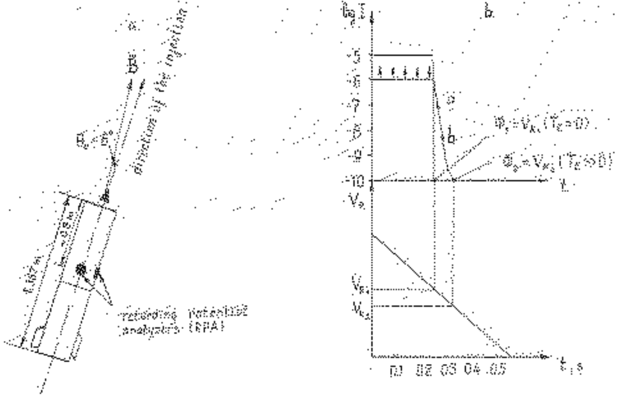

Fig. 1

a) the RPA positions on the rocket ;
b) the electron retardation curve diagram of the collector variation with the analyzing voltage V_R.

The ϕ value can be determined by the meaning V_R value corresponding to the instant of time of the collector current I jump ; in this case, the knowledge of value of neutralizing current $I_{\max}$ is not required. The thick curve in Figure 1b corresponds to the case when the collector current is created by cold ionospheric electrons, the thin curve corresponds to the case when the electrons are heated additionally. The electron heating as it is seen from the upper diagram of Figure 1b makes the current jump less sharp and, consequently, the determination of the ϕ value by the mentioned method becomes less definite.

The conditions of the measurements of retardation curves (the frequency of the collector current recording 30 Hz, the period of retarding voltage change $t = 0.64$ sec) were not suitable for the estimates of the potential during the short injection impulses with duration $\tau_2 = 0.02$ sec. Therefore this paper considers only the measurements made during the longest injection pulses τ_1 when the angle between the direction of the injection and the magnetic field θ_0 is 6° (see Fig. 1a) ; the angles between the magnetic field and the normal to each analyzer θ_g were also practically constant and close to 90° ($\Delta\theta_g = 84 \div 96°$).

The generator of analyzing voltages V_R was synchronized with the injector operation in such a way that during each long pulse each analyzer measured four retardation curves. It has already been mentioned that, to a certain extent, it is possible to observe the variations of the environment parameters and rocket potential during one injection pulse. On the Eridan rocket there was installed a powerful caesium plasma generator which however was switched on only during a part of the flight and injected the plasma flux with intensity 10A (Morozov *et al.*, 1978).

3. Measurement results

During the whole flight the currents in the analyzers were recorded only during the gun operation pointing to the fact that

a) for the switched off gun the rocket potential was lower than 9 V ;

b) in the interval between current pulses the electron fluxes with energies $E > 9$ V near the rocket were below the threshold sensitivity of the instruments.

The general character of retardation curves did not practically change when the injection energy was changed from 27 keV to 15 keV. The plasma generator switching on and off also influenced only slightly the general view of retardation curves. As an example, Figure 2 gives the types of retardation curves obtained during long pulses of the gun for different parts of the rocket trajectory.

Two scales of retarding voltages corresponding to electron RPA are plotted on the abscissa and the currents on the ordinates. As in both instruments V_R varied linearly with time, the curves of Figure 2 can be considered simultaneously as a time function during the interval equal to 0.56 sec.

It can be seen that during the decrease of the retarding potential there is always a sharp increase of currents in the interval 10^{-7} A to 10^{-6} A. It is easy to notice that these current jumps are observed in both analyzers at different instants but at the same value of V_R, marked V_R^*, V_R^{**} respectively.

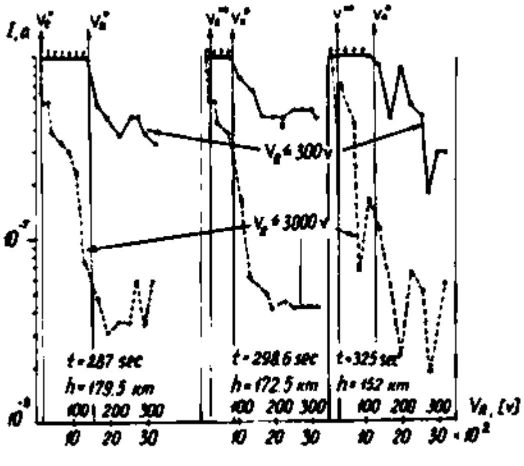

Fig. 2

The examples of electron retardation curves for the change of V_R from 0 to ~ 300 V and from 0 to ~ 3000 V.

For each RPA Figures 3 and 4 give the retardation curves for all long pulses. Every cycle consisting of four dependences $I = f(V_R)$ corresponds to one injection pulse τ_1.

The study of experimental data shows that in all cases in both devices a sharp decrease of the current from the value corresponding to the saturation to some value (at low altitudes below ~ 120 km). The cur-

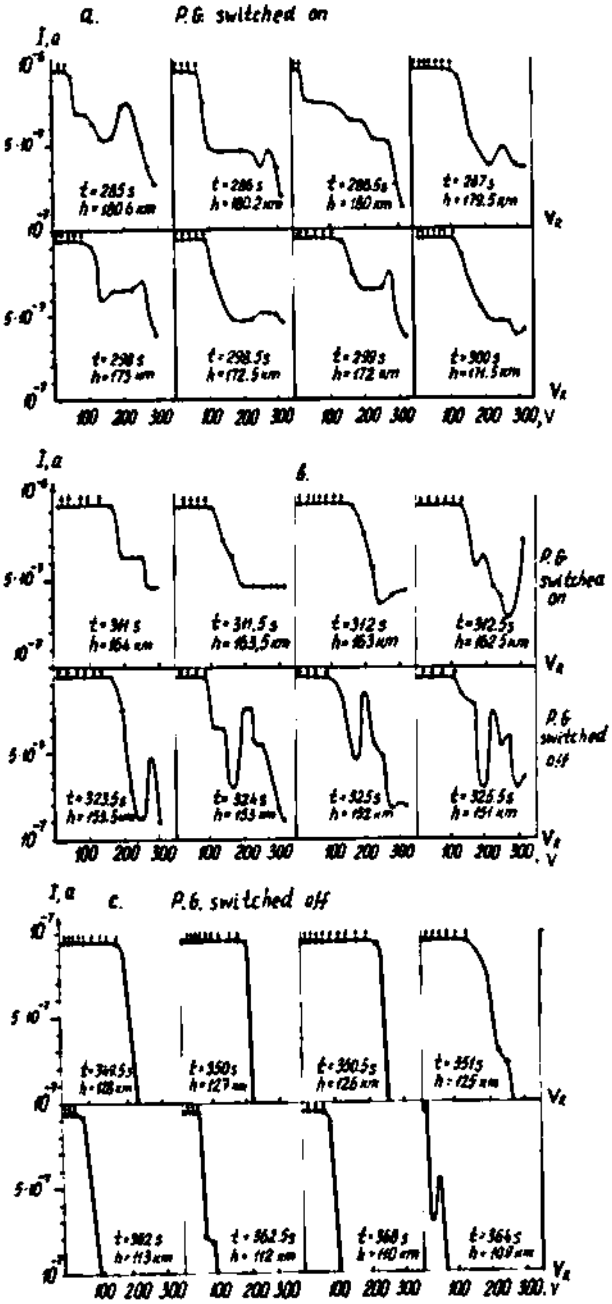

Fig. 3

The retardation curves for the RPA with $V_R \lesssim 300$ V.

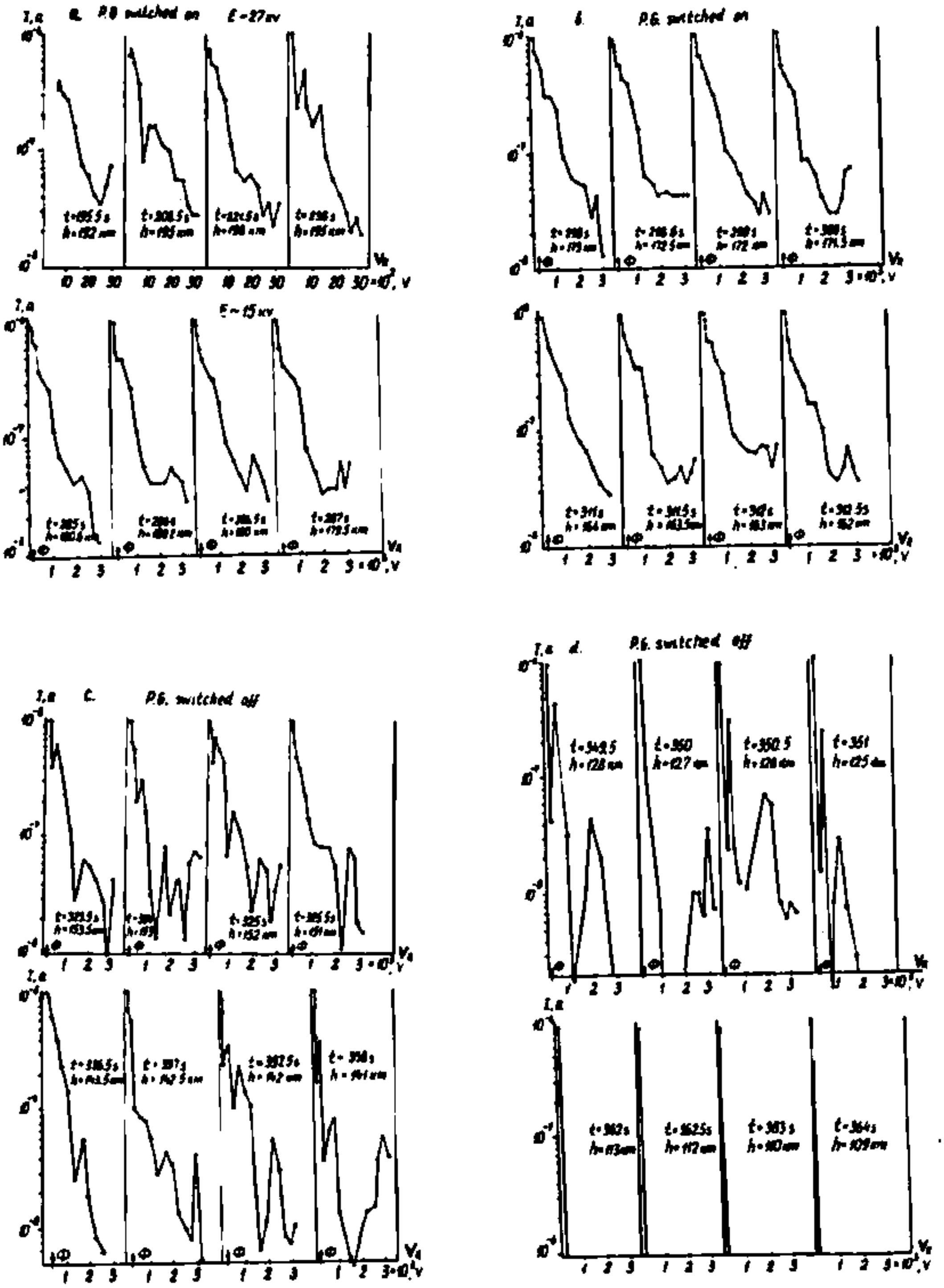

Fig. 4
The retardation curves for the RPA with $V_R \lesssim 3000$ V.

rent jump at which its value decreases to $I \lesssim 10^{-7}$ A is always observed when $V_R < 200$ V.

It can be assumed according to above concept of the possibility of determining the rocket potential from the retardation curve that the values V_R at the instants of collector current jumps to the value $I \gtrsim 10^{-7}$ A should correspond to the rocket potential relative to the environment.

The fact that the current jumps are observed in both analyzers not simultaneously (because the values $V_R < 200$ V are realized in these instruments at different time intervals) but for same values V_R ($V_R^* \cong V_R^{**}$) means that during one period of analyzing voltage the rocket electric potential does not practically vary.

At the heights $h \gtrsim 115$ km the current jumps are not so steep as they could be if during the electron injection the return electron currents to the rocket would be created only by cold ionospheric electrons accelerated to energy $e\phi$.

Besides the similarity of retardation curves during the injection pulse duration $\tau_1 = 2.56$ sec, i.e. during several revolution of the rocket rotating around its axis with the velocity 2.5 r.p. sec., shows that characteristics of electron fluxes coming to the rocket side surface do not depend on the variations of the RPA orientation relative to the geomagnetic field ($\Delta\theta_g = 84 \div 96°$), caused by the rocket rotation. The currant density on the rocket side surface always exceeds $2\,10^{-7}$ A/cm^2.

The altitude variation of the rocket electric potential value determined by currents jump according to the method described above is given in Figure 5, where each given ϕ value is averaged over data obtained from four retardation curves corresponding to one long injection pulse. The change of the rocket altitude during averaging did not exceed ~ 2 km. The scatter in the observed ϕ values (Fig. 5) during the time τ_1 (which is shown on Figure 5 by vertical bars) is probably caused by both possible variations of the injection current and the inaccuracy of determination of the collector current jump because of the heating of plasma surrounding the rocket.

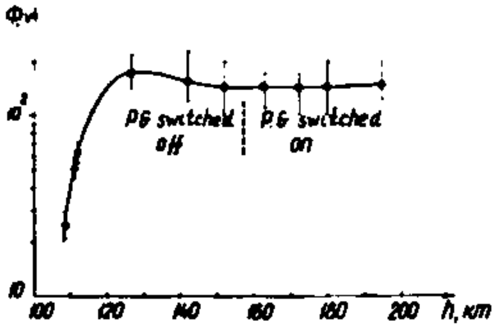

Fig. 5

The height dependence of the rocket electrical potential ϕ

The time of appearance of neutralization current after the beginning of the injection is less than 30 msec. The peculiar characteristic of the most retardation curves at the heights more than 115 km is the presence of currents created by electrons which energies exceed 200 V. It is also typical, that at the mentioned heights in the range of energies $E > 200$ eV there is a number of maxima and minima at the retardation curves. It is evident that if the recorded electron fluxes are time independent the retardation curves should be monotone for any differential electron energy spectrum. The presence of extrema in retardation curves and even more, that cases of episodic disappearance of fluxes with energies $E > 1$ keV (Fig. 4c and 4d) demonstrate considerable time fluctuations of recorded fluxes. It should be noticed, that the 'flat' area (parallel to the abscissa) of the retardation curve means the absence of electrons with energies corresponding to this part of retardation curve during V_R variations.

In this case the type of energy spectra and their fluctuations appearing mostly for $V_R > 200$ V are not connected with the rocket rotation. It can be also mentioned that the fluctuation amplitude increases for a switched off plasma generator, while the V_R values for which the current jump to $I \gtrsim 10^{-7}$ A is observed do not change.

The form of retardation curves considerably varies with the variation of the rocket height. The intensity of fluxes with energies $E \sim 1000$-3000 eV, as h decreases, begins to decrease and for $h < 125$ km practically disappears. At heights of about 140-125 km time variations of electron fluxes increase and during one cycle of retarding voltage, they periodically appear and disappear. Figure 6 gives height dependences of average collector currents corresponding to various intervals of V_R value. The averaging was made for one injection pulse $\tau_1 = 2.56$ sec i.e. by four retarding curves. So time fluctuations of each current-voltage characteristic were also averaged. Higher than ~ 160 km the average fluxes in all energy ranges have not prac-

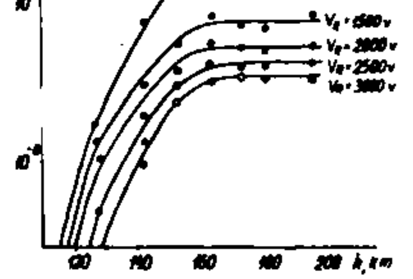

Fig. 6

The height dependence of electron fluxes with $E > e\phi$

tically varied with the height ; beginning with about 160 km, for the height decrease, they begin decreasing rather sharply. At heights $h \lesssim 120$ km the energy of observed particle fluxes did not exceed ~ 100 eV.

4. Discussion

The consideration of the measurement results given above makes it possible to conclude that electrons always gathered on the rocket side surface where the analyzers were mounted. This surface is practically parallel to the magnetic field. It follows from Figure 5 that the rocket potential in this experiment at the heights of about 130-190 km did not exceed 150 V and decreased to 20 V near 100 km.

It should be recalled that the frequency of the RPA current recording in the Araks experiments (30 Hz) did not make it possible to judge of the rocket potential during the first 30 msec after the beginning of the injection but it is clear that after these 30 msec during long injection pulses with $\tau_1 = 2.56$ sec the rocket potential was relatively stable. The plasma generator operation did not practically affect the rocket potential.

For comparison Table 1 gives some characteristics of other active experiments carried with the use of different means of neutralization (Hess *et al.*, 1971 ; Hendrickson *et al.*, 1971 ; Mc Entire *et al.*, 1974 ; Israelson and Winckler, 1979 ; Winckler *et al.*, 1975 ; Hendrickson *et al.*, 1976) and without them (O' Neil *et al.*, 1978 a ; 1978 b). Almost in all these experiments the data on the rocket electric potentials were obtained by probe methods (by the use of RPA or Langmuir probes), with as explicit or implicit the assumption of the applicability of the Langmuir probe theory at all heights considered.

The experiment main parameter affecting ϕ value is naturally the injected electron current (it has been shown above that the change of electron energy from 15 keV to 27 keV only slightly affects the current-voltage characteristic of the electron RPA and the ϕ value respectively). Table 1 shows that in different experiments injection currents differed almost by three orders of magnitude but the rocket potential in all cases did not exceed 200 V.

For the heights $h < 120$ km the type of height dependence of ϕ given on Figure 5 is in a good agreement with the height variation of the potential in the PRECEDE experiment (O' Neil *et al.*, 1978 a).

Table 1

The data of the experiment and name	The experiment condition			Maximum	Authors References
	Injection Current, A	Injected Energy, keV	Maximum height, km	Potential, V	
1.1969	0.0015-0.5	1.25-10	270	Low potential	W.N. Hess *et al.*, 1971.
ECHO-I VII. 1970	0.075	34-43	350	100	R.A. Hendrickson *et al.*, 1971 R.W. Mc Entire *et al.*, 1974
ECHO-II IX. 1972	0.08	7-32.5	264	80	J.R. Winckler *et al.*, 1975
ECHO-III IV. 1974	0.012 0.07	29-23 32-36.5 38-41 38-43	275	100	R.A. Hendrickson *et al.*, 1976.
PRECEDE;X.1974	0.08	2.5	120	33	R.R. O'Neil *et al.*, 1978 a.
ARAKS I. 1975	0.5	15 27	190	150	This paper.
EXCEDE IV. 1975	5 10	3	135	200	R.R. O'Neil *et al.*, 1978 b.
ECHO-IV I. 1976	0.02-0.11	8-18 20 30-40	215	100	G.A. Israelson and J.R. Winckler, 1979.

In the considered height range the $\phi(h)$ dependence in each experiment shows the essential effect of the neutral atmosphere density on ϕ value. By the use of the Langmuir probe theory by O'Neil *et al.* (1978a), the theoretical estimate of the rocket potential in the stationary state is made under the assumption of increasing charged particle density in the near-rocket region due to the ionization of the medium by the beam ; a good agreement with the experiment was obtained. The similar estimate for the Araks experiments (without taking into account the electron heating near the rocket) also gave the agreement with results of measurements at heights of about 100 ÷ 120 km but showed an essential discrepancy with experimental data for $h > 120$ km. There, as is seen in Figure 5, the ϕ values did not practically depend on h and according to the above mentioned estimation the monotone increase of the potential continued with the height in accordance with the decrease of the neutral gas density.

The problems of neutralization in the ionosphere of beam up emitting body were considered in many papers (Israelson and Winckler, 1979 ; Winckler *et al.* 1975 ; Beard and Johnson, 1961 ; Parker and Murphy, 1967 ; Linson, 1969 ; Galeev *et al.*, 1976 ; Cartwright *et al.*, 1978 ; Volokitin and Mishin, 1978). However a generally accepted explanation of the neutralization mechanism is still absent. The hypothesis about the appearance of the plasma-beam discharge in the near-rocket region developed by Galeev *et al.* (1976) explains well comparatively low experimental values of the rocket stationary electrical potential only for the heights < 115 km, where the neutral gas density near the rocket is $N > 10^{12}$ cm^{-3}.

Apparently for the explanation of the observed height ϕ dependence the effect of increase of secondary particle fluxes due to the ionization of the surrounding neutral atmosphere by multiply scattered injected electrons and also by the return particle fluxes (O' Neil *et al.*, 1978 a ; 1978 b) should be taken into account together with the appearance of the plasma-beam discharge (Galeev *et al.*, 1976). Such factors as the drift of electrons near the vehicle in the crossed electric and magnetic fields, the connection of the near-rocket region through the magnetic field line with the lower ionosphere, where the mean free path of electrons is much less than the Larmor radius, the increase of the current of neutralization due to the heating of ionosphere electrons (Hess *et al.*, 1971 ; Volokitin and Mishin 1978 ; Gringauz and Shutte, 1976 b) and the corresponding formation of the near rocket disturbed region of a high conductive plasma should be also taken into account. The degree to which each mentioned factor effects the processes of rocket neutralization varies with the height.

The type of the current-voltage characteristics recorded makes it possible to conclude that in the whole investigated height range the neutralization was provided by electron fluxes with energies $E < e\phi$.

As it was shown in Figure 4 and 6 during almost all the flight of the Eridan rocket particle fluxes with energies $E > e\phi$ were observed.

It is known that on board the rocket several instruments for the measurements of charged particle fluxes were mounted (Barthe *et al.*, 1978 ; Volkov *et al.*, 1978 ; Managadze *et al.*, 1978) ; among them only "SERBE' (Managadze *et al.*, 1978) (Ushba) instrument operated in the energy range from 1 to 16 keV and partially overlapped the energy range of the retarding potential analyzer (in the interval 1÷ 3 keV). The comparison of the described results with the data of the instrument 'SERBE' given in Managadze (1977) shows that their agreement is only partial.

During long injection pulses the instrument 'SERBE' recorded particle fluxes with energies from 2 to 3 keV throughout the flight. It was difficult to compare these data in more detail because of the essential difference between the energy resolution of these instruments. In addition the energy spectra given in the paper of Managadze (1977) represent the result of the summation of a number of spectra with duration of 10 msec each, recorded during the injection pulse $\tau_1 = 2.56$ sec (near the altitude shown at each spectra) but they did not obviously reflect the essential time fluctuations of electron fluxex with energies of about 1÷3 keV. Besides, unlike the data given in this paper, the instruments 'SERBE' did not record the electron fluxes with energy from 1 to 2 keV, but recorded particle fluxes with $2 < E < 3$ keV at the height $h \sim 100$ km.

In the other rocket experiments with electron injections the electron fluxes were also observed whose energies exceeded essentially the values determined by the rocket potential. So, for example in the cases of Israelson and Winckler (1979) and of Winckler *et al.*, (1975), during the injection pulses, the electron fluxes with continuous energy spectrum were recorded from the energy determined by the rocket potential to the injection energy. For electron injections at 90° to the rocket axis, Winckler *et al.* (1975) taking into account the relative positioning of the detectors and the gun made a conclusion that the fluxes observed are caused by multiple scattering of injected electrons from the rocket body during their motion along Larmor orbits. Israelson and Winckler (1979) also note that such an explanation does not fit the injection upwards, along the rocket trajectory.

It can be assumed that at heights $h > 130$ km for which the collisions with neutrals can not be taken into account the observed increase of near-rocket plasma heating is determined by the development of parametric instabilities of Langmuir waves disturbed by the beam in plasma (Alterkop *et al.*, 1977). In this case the electron fluxes with $E > e\phi$ can be the result of the "acceleration" of ionosphere electrons in the process of resonant particle diffusion to higher velocities and of a plateau set up in the distribution function curve. Such a mechanism makes it possible to explain the observed time fluctuations of fluxes with $E > e\phi$ as low frequency oscillations of densities due to the development of aperiodic $(\omega < \omega_c)$ instabilities of beam-generated Langmuir waves (Volokitin and Mishin, 1978 ; Alterkop *et al.*, 1977).

The above described data apparently show that the electron RPA installed on board the rocket with the electron beam injector yields information not only about rocket electric potential but on physical processes in the surrounding plasma as well.

Further, when similar measurements are made to enhance possibility of observing electron flux variability with $E > e\phi$ it is reasonable to increase the time resolution of analyzer collector current recording and to expand the dynamical range of collector currents measured to determine the neutralizing current density and range of analyzed energies, i.e. the maximum retarding potential.

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