ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2021, Vol. 57, No. 5, pp. 731–744. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Fizika Zemli, 2021, No. 5, pp. 169–183.

Physical Effects Arising from the Motion of Plasma Flows in the Ionosphere[1]

B. G. Gavrilov[a], * and Yu. V. Poklad[a]

[a] *Sadovsky Institute of Geosphere Dynamics, Russian Academy of Sciences, Moscow, 119334 Russia*

**e-mail: boris.gavrilov34@gmail.com*

Received February 26, 2021; revised March 28, 2021; accepted April 1, 2021

Abstract—The occurrence and evolution of plasma fluxes in the ionosphere is one of the factors that have a significant impact on the dynamics and state of the geophysical environment. The study of plasma and magnetohydrodynamic effects arising from the motion of plasma jets in real space is complicated by the scale of the phenomenon and the complex nature of the background environment, which is a non-stationary system of interacting neutral and partially or completely magnetized charged particles. The creation of theoretical models of this phenomenon is also completely unsolved scientific task. Under these conditions, controlled ionospheric plasma experiments are of great importance. The results of active rocket experiments obtained over the past few decades have made it possible to study the processes of magnetohydrodynamic interaction between a high-velocity plasma and the geomagnetic field, the generation of electromagnetic and MHD waves, optical radiation in the visible, UV and IR ranges, background gas ionization, the emergence of complex systems of electric fields and currents, the acceleration of charged particles, and other phenomena. The article discusses the current physical concepts developed from the analysis of the available experimental data, as well as the tasks and possibilities of new active experiments.

Keywords: ionosphere, magnetosphere, plasma flows, geomagnetic field, field-aligned currents, active rocket geophysical experiments

DOI: 10.1134/S1069351321050049

INTRODUCTION

Plasma fluxes (PF) of different scales, densities, compositions, velocities, and lifetimes are one of the main elements of outer space, the magnetosphere of the Earth and planets, the ionosphere and the atmosphere. Their origin, movement, evolution and decay, which have a huge impact on the processes in the environment, is one of the fundamental problems of astrophysics and geophysics. The formation of the magnetosphere is already the result of the interaction of the solar coronal plasma flow and the geomagnetic field. When the solar wind flows around the magnetosphere, the plasma diffuses into the magnetic field and a boundary layer is formed, where a viscous interaction is carried out with the transfer of momentum from the solar wind to the magnetosphere. In the boundary layer, the plasma flow directed across the magnetic field induces a field—$\mathbf{V} \times \mathbf{B}/c$, which leads to the generation of pairs of field-aligned currents (FAC) on the morning and evening sides of the magnetosphere. Each pair of currents closes in the polar ionosphere along the interface between the closed magnetic field lines and the lines going into the tail.

The experimental study of the currents in the boundary region is extremely difficult, the PF are very sensitive to the rapidly changing of the interplanetary magnetic field, as a result of which the morphology and role of the boundary FAC remain insufficiently studied. It is too difficult to ensure the simultaneous location of a large number of spacecraft at critical points in the lobe part of the magnetosphere and the geomagnetic tail to register the generation of fields and currents during plasma injection and their connection with the processes in the head part of the magnetosphere. Meanwhile, the study of FAC generated by a plasma jet during a magnetic storm is necessary to understand the physics of plasma capture in a ring current. It is, apparently, the deceleration of the plasma jet, which transmits an impulse to the ionosphere through FAC. The currents are generated by the Hall electric field directed towards the Earth along the tail. This $E = \frac{j \times B}{nec}$ field is caused by a current-carrying electron flow in the current layer of the magnetic tail. A circuit is created in which FAC are closed in the ionosphere due to the Pedersen conductivity, and an electrojet occurs due to the Hall conductivity. The amplification of the western electrojet associated with an

---

[1] The article was translated by the authors.

increase in the magnitude of FAC is the main magnetic disturbance in the polar ionosphere.

The interaction of plasma fluxes with the geomagnetic field causes a number of environmental effects that can significantly affect the energy characteristics, state, and dynamics of the Earth's ionosphere and upper atmosphere. The complexity of studying these processes in a real space environment leads to the fact that the question of changes in the parameters of the Earth's ionosphere, which may occur as a result of Joule heating and ionization of the ionosphere at altitudes of ~100 km during the flow of Pedersen currents in this region or during the precipitation of high-energy electrons accelerated in layers of FAC, remains poorly understood. PF can also occur and affect processes in the magnetosphere and ionosphere during the entry of large meteorites into the Earth's magnetosphere, rocket launches, and high-altitude explosions. One of the main channels for the transfer of energy, momentum, and matter from the magnetosphere to the lower layers of the ionosphere is PF (Kamide and Baumjohann, 1993). In the plasmosphere and the tail of the magnetosphere, FAC causes the acceleration of charged particles, the heating and movement of the ionosphere, and other effects observed in the auroral regions of the Earth during magnetic storms and substorms. These effects have been studied and described in numerous papers (Alfven, 1983; Angelopoulos et al., 1992; Danji, 1961; Baumjohann et al., 1990; Petrukovich et al., 2001; Lysak, 1985; Iijima and Potemra, 1976; Sergeev et al., 2000; Shiokawa et al., 1997; Zetzer et al., 2004). To a lesser extent, the influence of FAC on the dynamics and evolution of the plasma flows themselves has been studied. It is obvious that the generation of FAC should lead to energy dissipation and deceleration of the magnetospheric plasma and affect the dynamics of plasma flows, including those injected from the tail of the magnetosphere. The present concepts and theoretical models describing the dynamics of sporadic plasma flows in the magnetosphere tail still have no direct experimental evidence. At the same time, the quantitative study and simulation of this physical effect can be quite effective in controlled laboratory and ionospheric plasma experiments.

Over the past decades, many active space experiments have been conducted with the injection of neutral gas, plasma streams, or charged particle beams (Adushkin et al., 1993; Bernhardt et al., 1987; Delamere et al., 1996; Dimonte and Wiley, 1991; Fuselier et al., 1994; Pilipenko et al., 2005; Scholer, 1970; Swenson et al., 1992; Valenzuela et al., 1986). Their capabilities were limited to a certain extent by the fact that the measurements were carried out at one or two points, which did not allow obtaining reliable data on the evolution and dynamics of plasma flows and processes accompanying the movement of plasma in the environment.

We can identify some of the most significant physical problems that arise in the study of the processes of the origin and evolution of FAC and their interaction with the environment. These include the displacement of a moving dense plasma of the magnetic field, the electric polarization of the plasma, the occurrence of PF and their effect on the dynamics (braking) PFs, generation of plasma and electromagnetic waves, heating, excitation and ionization of background gas, diffusion of an external magnetic field into a plasma formation, evolution of a magnetized plasma.

The paper discusses the methods and results of studying these issues in active rocket plasma experiments.

EVOLUTION OF PLASMA FLOWS IN THE MAGNETIC FIELD AND BACKGROUND PLASMA

Let us briefly consider the main processes of interaction of PF with the magnetic field and environment. One of the main parameters determining the interaction of moving plasma with the magnetic field is the ratio of the kinetic energy of PF to the magnetic field energy density $\beta = n_i m_i V^2 \bigg/ \left(\dfrac{\mathbf{B}^2}{8p}\right)$, where n_i, m_i and V are the density, mass, and velocity of the jet ions, and B is the magnetic field induction. Depending on the ratio of the density of the PF and the surrounding gas and the value of the parameter β, several scenarios of the interaction of PF and the magnetic field can be considered (Gavrilov et al., 1995).

If the energy density of the plasma jet exceeds the energy density of the magnetic field ($\beta > 1$), the plasma displaces the magnetic field, forming a diamagnetic cavity. On the sides of the jet, layers of space charge are formed, and an electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$ arises, preventing further deflection of the particles. The jet moves across the magnetic field along a straight trajectory. The presence of background plasma leads to the generation of Alfven waves propagating along the magnetic field. The Alfven wave carries a current $i = (c^2/4\pi V_A)E$, where V_A is the Alfven velocity. In the space between a pair of sheets of oppositely directed FAC, the electric field engages the background plasma in motion (Sobyanin et al., 2002).

This process leads to the deceleration and deflection of the PF, the diffusion of the magnetic field into the plasma, and its erosion. In the case of a low plasma density and a strong magnetic field, the plasma jet stream degenerates into a Larmor rotation of charged particles moving away along the magnetic field (Gavrilov et al., 1994; 1998).

These scenarios can be observed during the movement of PF with the corresponding parameters for a sufficiently long time, or, as happened in most space plasma experiments, they can be realized as successive

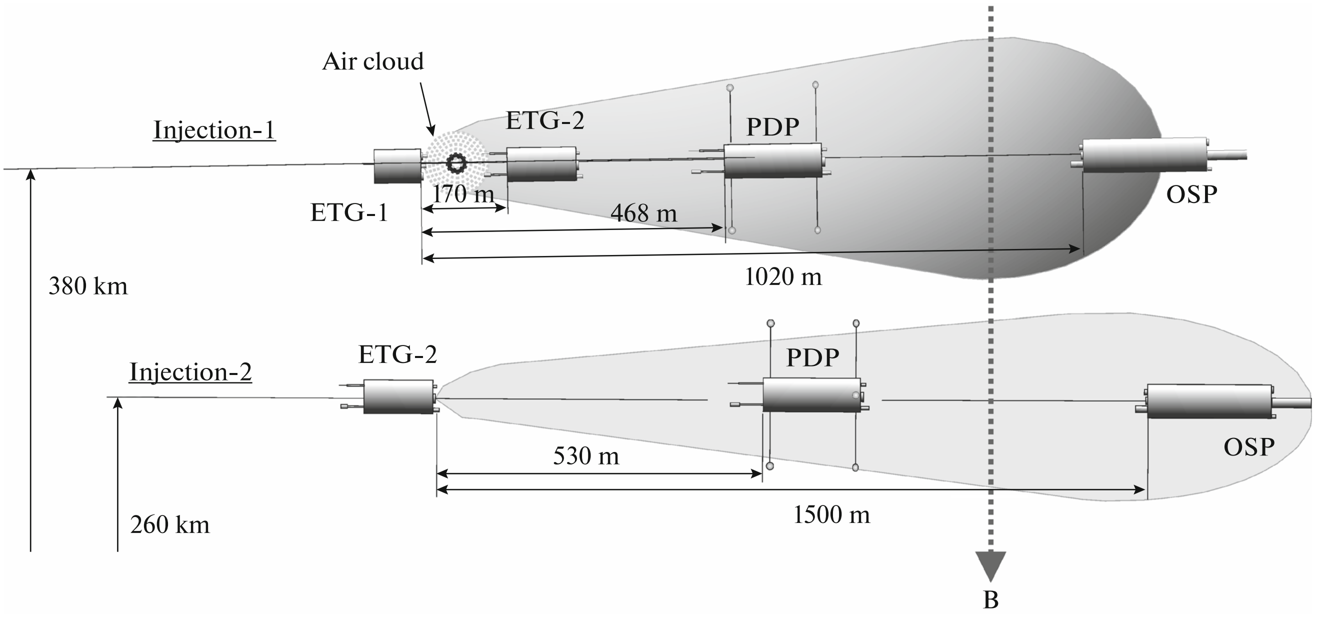

Fig. 1. Scheme of the NS experiment.

stages of the evolution of a plasma jet in a magnetic field.

A recent review (Haerendel, 2019) provides a very complete analysis of the tasks, methods, and results of space plasma experiments. The possibilities of most of them were significantly limited by the fact that the measurements were carried out at one or two points in the vicinity of the plasma formation, which did not make it possible to obtain any complete information about the dynamics of PF and processes in the environment. In 1999 two Russian-American active rocket geophysical experiments "North Star" were conducted (Gavrilov et al., 2003; 2004; Erlandson et al., 2002; Delamere et al., 2004; Pfaff et al., 2004), scenarios and measurement capabilities of which were specially developed for the study of different stages of interaction of plasma fluxes of different densities in the ionosphere. The scenarios of the evolution of high-velocity plasma jets in a magnetic field are discussed below by the example of the results of this experiment with the use of data from other space experiments with the injection of plasma-forming substances into the Earth's ionosphere.

THE "NORTH STAR" EXPERIMENT

The unique scheme of the North Star experiment (NS) for the first time made it possible to carry out complex measurements of the parameters of a plasma jet at three points of the trajectory in the ionosphere and to conduct the most complete plasma diagnostics of the behavior of dense pre-Alfven plasma jets with $\beta > 1$ and $\beta < 1$ injected into the Earth's ionosphere perpendicular to the geomagnetic field. Data on anomalous diffusion, the structure of the front of a diamagnetic cavity, magnetohydrodynamic disturbances in the background plasma, and polarizing electric fields in a plasma jet generating FAC are obtained.

Two injections were carried out at altitudes of 360 and 280 km. The experiment was able to obtain data on the dynamics and evolution of the plasma flow, the composition and energy of charged particles, changes in the magnetic and electric fields in the jet and its surroundings from measurements on four modules at distances from 170 to 1500 m from the plasma source (Fig. 1). The Black Brant XII rocket with plasma generators and scientific diagnostic equipment was launched on January 22, 1999 at the Poker Flat test site. The experimental scheme provided injection of ionized aluminum jets perpendicular to the geomagnetic field. During both injections, optical measurements were carried out from the US MSX satellite and from the Earth's surface.

Explosive plasma generators installed on ETG-1 and ETG-2 modules were used as plasma jet sources. In the generators (Adushkin et al., 2000), the principle of evaporation of a solid porous substance and acceleration of vapors by a shock wave converging to the axis, excited by the explosion of a charge of a powerful explosive, is used. Porous aluminum was used as the working substance. Ground tests of plasma generators showed that the mass of the jet does not exceed 30 g, and the maximum speed of expansion is 42 km/s. The energy of the plasma jet is 5 MJ. Almost all the energy and mass of the jet are concentrated in the angle of 30° (Erlandson, 2002).

During the first injection (hereinafter referred to as I-1), 11.5 g of compressed air was released 200 ms

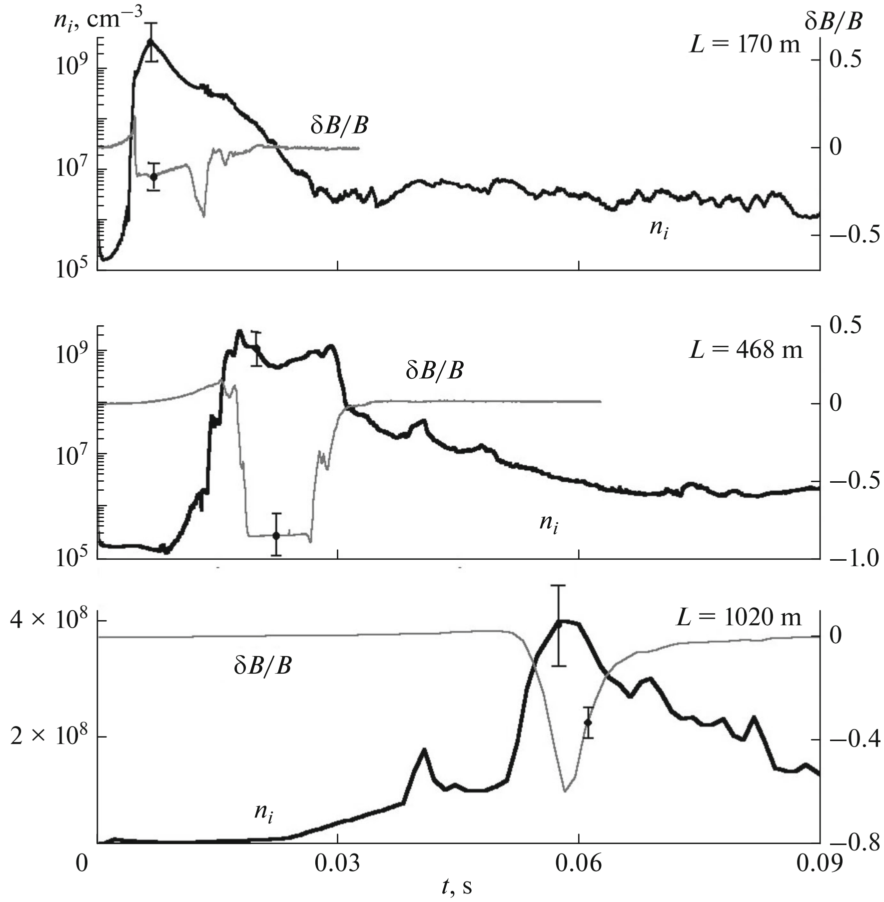

Fig. 2. Experiment NS I-1. Plasma density (bold curve) and magnetic field change (thin curve) at a distance of 170 m (upper panel), 468 m (middle panel) and 1020 m (lower panel) from the plasma generator.

before the plasma jet exit, creating a cloud of neutral gas in the path of the jet (Erlandson et al., 2002). The goal of creating the cloud was to increase the ionization of the plasma by interacting of the plasma jet with neutral air molecules. Although the mechanism of the growth of ionization of the moving plasma in its interaction with the background neutral gas remains not fully understood, the measurements showed that a significant increase in plasma density was observed when the plasma was released into the air cloud. The second plasma injection (I-2) was performed at an altitude of 280 km. In this case, a plasma generator installed on the ETG-2 module was used. Unlike the first experiment, I-2 was conducted in a natural atmosphere.

The results of measuring the plasma density and magnetic field variations in the jet in the I-1 experiment at distances of 170, 468 and 1020 m from the plasma generator are shown in Fig. 2. The density of the background plasma before injection was ~7×10^4 cm^{-3}. A significant increase in the plasma density at a distance of 170 m from the jet source is recorded 4 ms after the detonation, that corresponds to the plasma velocity of ~42 km/s. The maximum plasma density of ~3×10^9 cm^{-3} is reached at 7 ms. Then n_i gradually decreases. The sensors of the ETG-2 module registered only the variation of the Y-component of the magnetic field that was perpendicular to the direction of the undisturbed magnetic field at the time of injection.

A sharp increase in the plasma density at a distance of 468 m from the plasma generator was registered at 13.7 ms, which corresponds to an average velocity of 34 km/s. High-frequency oscillations of the probe current are observed at the front. The maximum density is registered at 17.7 ms. Further, the plasma density decreases, and a second peak of $n_i = 10^9$ cm^{-3} is registered at 29 ms. The ion density gradually decreases. At a distance of 468 m from the explosive generator, the displacement of the magnetic field was observed for all three components. The maximum compression of the magnetic field (~15%) was registered at the leading edge of the diamagnetic cavity at the time of 15.4 ms. Then a sharp decrease in the magnetic field begins.

The front of the plasma cloud at a distance of 1020 m from the plasma generator is recorded at 50.9 ms which corresponds to an average velocity of 20 km/s. The maximum density of $n_i = 4 \times 10^8$ cm^{-3} is reached at 57.3 ms. Dense plasma with a $n_i > 10^6$ cm^{-3} is observed for 400 ms. In front of the jet, there is a slight increase in the magnetic field due to the propagation of a magnetosonic disturbance in the ionospheric plasma. The maximum compression of the magnetic field is reached at 50.4 ms. Then the magnetic field begins to decrease up to the value of 0.2 G for 58 ms. The duration of the diamagnetic signal coincides with the region of the maximum plasma density. The degree of displacement of the magnetic field does not exceed 60%. The estimate of the plasma density from the pressure balance at the boundary of the diamagnetic cavity agrees within the measurement error with the data of the Langmuir probes.

In Figure 3, the changes in the plasma density and magnetic field in the jet are shown together with the measured transverse electric field in the plasma jet. At a distance of 468 m an almost complete displacement of the magnetic field by the plasma jet was observed. At the same time, in the region of the diamagnetic cavity, the plasma density profile has a characteristic two-peak structure, which may be associated with the formation of the shell structure plasma cloud. The formation of a plasma envelope in a moving plasma with $\beta > 1$ was observed in the AMPTE space experiment (Bernhardt, 1987) and in numerical simulations (Papadopoulos, 1991).

Raizer (1963) considered the problem of expanding of superconducting ball into a vacuum in the presence of a magnetic field. It was shown that a magnetic field compression of $\delta B/B_0 \approx 50\%$ should be observed in front of the plasma front. In our case, the degree of compression of the magnetic field at the front of the diamagnetic cavity does not exceed 15%. The weak compression of the magnetic field is probably due to the fact that the decelerating plasma flow moves at a pre-Alfven speed. In this case, magnetohydrodynamic waves transfer the energy of the perturbation of the magnetic field with the Alfven velocity in the background plasma to large distances from the jet, reducing the effect of compression directly in front of the jet.

The equation of the pressure balance at the boundary of a diamagnetic cavity can be written as

$$n_i m_i V^2 + \frac{B_i^2}{8\pi} = \frac{B_0^2}{8\pi}, \tag{1}$$

where n_i, m_i and V are the density, mass, and velocity of the ions, B_0 is the undisturbed magnetic field, and B_i is the magnetic field in the jet. At a jet velocity of about 40 km/s, to displace the magnetic field, the ion density should be 2×10^9 cm^{-3}, which is in good agreement with the data of the probe measurements. The boundaries of the cavity coincide with the region of the density of $n_i = 5 \times 10^8$–3×10^9 cm^{-3}.

The results of the measurement of the electric field in the plasma flow are consistent with the data of the magnetic field registration (Pfaff et al., 2004). The electric field component E_y, perpendicular to the jet velocity vector and to the magnetic field measured at a distance of 468 m from the plasma generator, is shown in the lower panel of Fig. 3. The electric field is generated both in front of the diamagnetic cavity and immediately behind it. From a time of ~17 ms E_y rapidly decreases to zero (inside the diamagnetic cavity) and remains so until t ~33 ms. Then the magnetic field penetrates into the plasma stream, and in this region the electric field E_y arises again. A gradual decrease in E_y is observed, which is associated with a decrease in the velocity of the plasma jet. The figure shows that in I-1 the experimental values of the transverse electric field practically coincide with the calculation data according to the formula $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$, where $\mathbf{V}$ is the time–of-flight velocity.

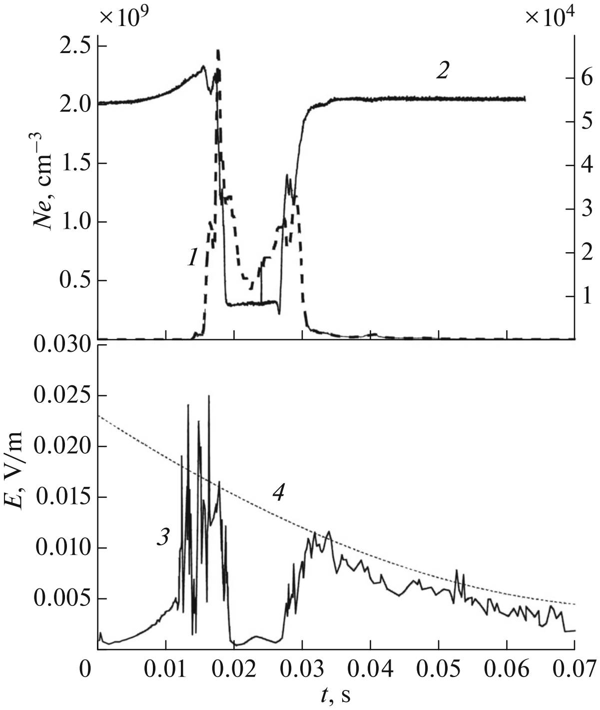

Fig. 3. Results of measurements of the plasma density (*1*), variations of the magnetic field (*2*), the electric field in the jet (*3*), and the calculated value of the electric field (*4*) at a distance of 468 m from the plasma generator in the NS I-1 experiment.

Figure 4 shows the change in the density of the plasma jet in I-1 when it propagates at a distance of 170, 468 and 1200 m from the plasma source. Estimates show that the drop in jet density corresponds to an increase in the volume of plasma cloud. The estimation of the time-of-flight velocity of the jet at the ion dencity level of 5×10^8 cm^{-3} shows that the velocity of the leading edge decreases approximately twice at a distance of about 1 km, while the velocity of the trailing edge of the jet remains almost constant with a tendency to increase. If this is not the result of a mea-

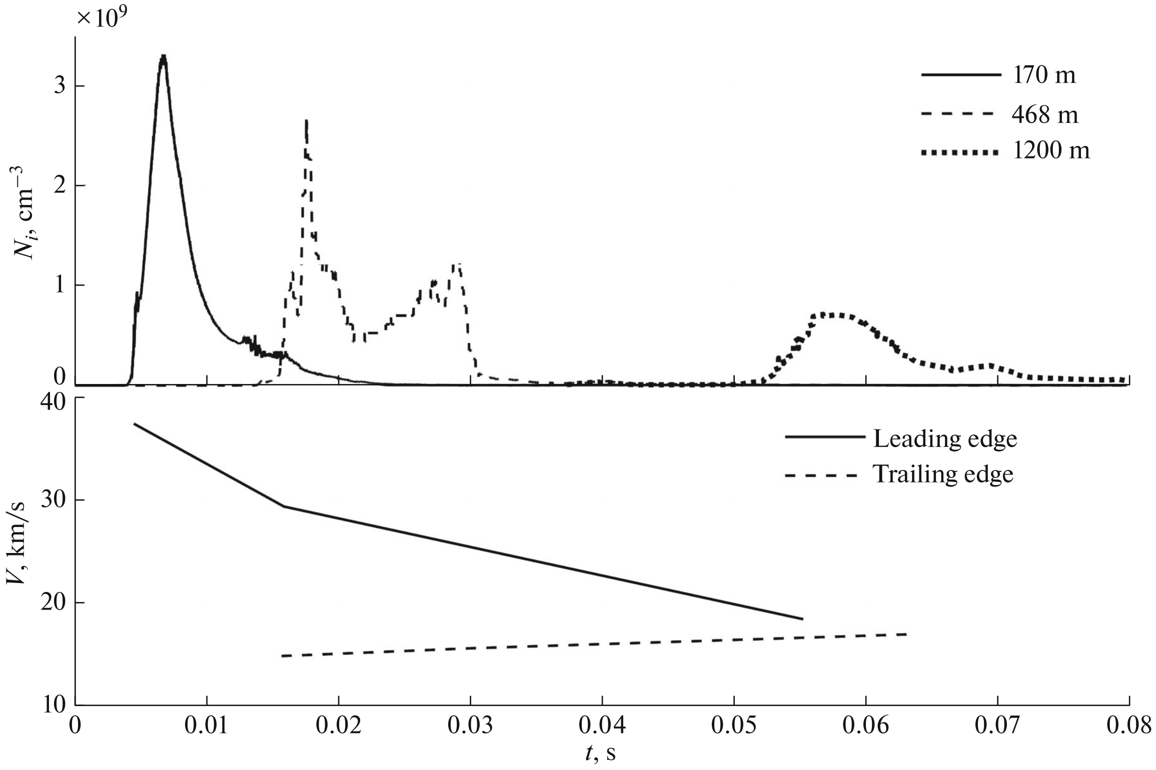

Fig. 4. Results of measurements of the plasma density in the I-1 experiment at different distances from the injector (upper panel) and the velocity of the leading and trailing edges of the plasma cloud at a density level of 5×10^8 cm^{-3} (lower panel).

surement error, the acceleration of the trailing edge may be due to the action of the trapped electrons of the background gas.

The motion of a homogeneous jet is described by the equations of a two-liquid MHD:

$$m_i dV_i/dt = eE + e(V_i \times B)/c + (V_e - V_i)m_e/\tau, \quad (2)$$

$$m_e dV_e/dt = -eE - e(V_e \times B)/c - (V_e - V_i)m_e/\tau. \quad (3)$$

The possible influence of the background plasma on the dynamics of the plasma jet with $\beta > 1$ may not be taken into account, since the gas-kinetic pressure of the background plasma is significantly lower than the pressure of the magnetic field. In this case, the kinetic energy loss of the plasma cloud propagating in the background plasma will be almost the same as in the absence of a background medium.

It is known that one of the most effective factors for deceleration of the plasma flow in the magnetic field is the FAC (Gavrilov et al., 1994). If the energy density of the plasma jet exceeds the energy density of the magnetic field ($\beta > 1$), the plasma displaces the magnetic field, forming a diamagnetic cavity. There is an electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$, which prevents further deflection of the particles. In this case, the plasma flow moves across the magnetic field along a straight trajectory with almost no braking. If this process occurs in the background plasma, the electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$ leads to the generation of the Alfven waves propagating along the magnetic field. The electric field engages the background plasma in motion, which reduces the plasma flow velocity. However, at time 0.025...0.027 s, the magnetic field is displaced from the jet, which leads to the absence of a polarizing electric field in the jet and, consequently, FACs that could lead to an effective deceleration of the plasma flow. However, there is a noticeable deceleration of the plasma. This means that some other braking mechanism is in effect at this time.

Such a mechanism may be the effect on the dynamics of the plasma flow of particles reflected from the leading edge of the jet. It is shown in (Raizer, 1963) that when the charged particles are reflected from the moving boundary of a diamagnetic cavity, they lose their kinetic energy. In the NS I-1 experimental confirmation of the possibility of implementing of this effect was obtained. Plasma measurements on board the PDP module located at a distance of 468 m from the plasma source, were carried out not only by Langmuir probes, but also by electrostatic electron (MESA and SESA) and ion (IESA) analyzer (Lynch et al., 2004). The device allowed to obtain data not only on the energy, but also on the pitch-angular distribution of charged particles. The interpretation of the entire set of data obtained by these devices is not the task of this article. Note only that the ions moving

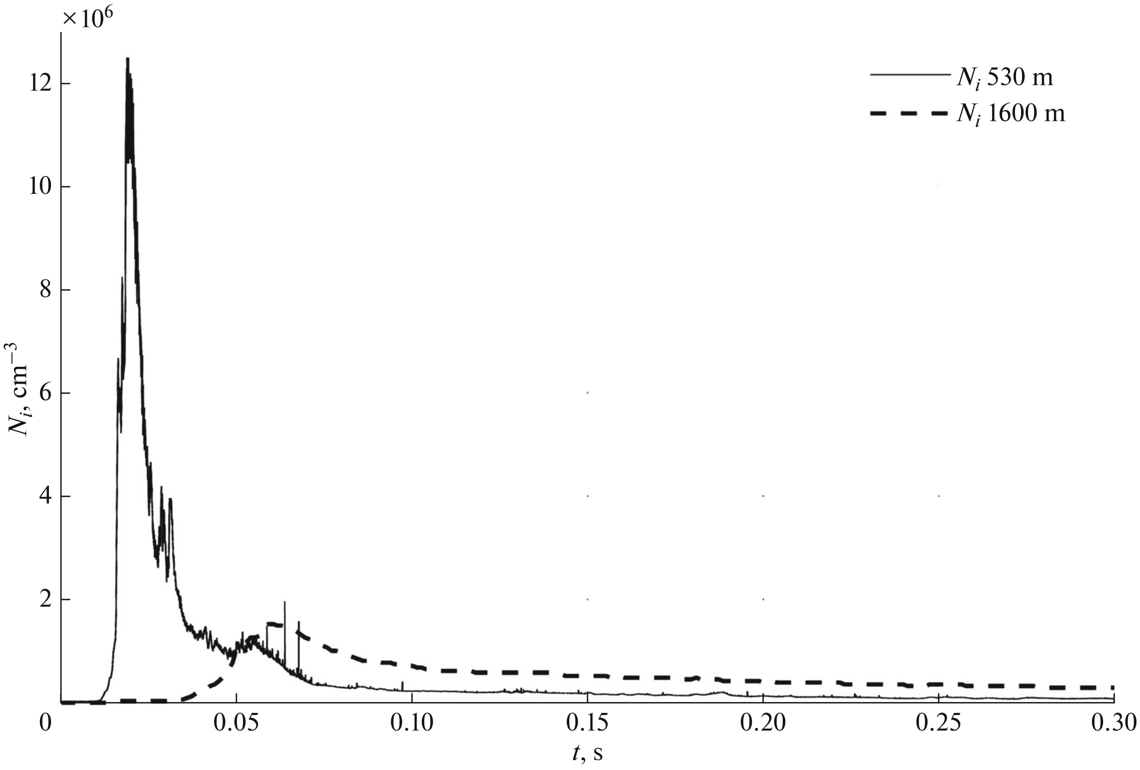

Fig. 5. Results of measurements of the plasma density in the I-2 experiment at a distance of 530 and 1600 m from the injector.

towards the plasma flow were actually detected in the experiment. Thus, the possibility of loss of the kinetic energy of the flow as a result of reflection of charged particles from the moving front of the diamagnetic cavity can be considered as a real mechanism of plasma deceleration in the I-1 experiment.

A completely different dynamics of the plasma jet was observed in the I-2 experiment. Note that the plasma flow velocities in I-1 and I-2 at a distance of ~500 m were almost equal, despite the fact that the plasma density in I-2 was two orders of magnitude lower than in I-1 (Fig. 5). The decrease in the plasma density in the second experiment was due to the fact that the I-2 was carried out in the background ionosphere and there was no additional ionization associated with the injection of the jet into a dense air cloud, as it occurred in I-1. On a path of 1 km, the plasma density drops by about an order of magnitude.

The data of measurements of the ion density and magnetic field in the jet show (Fig. 6) that at a distance of 537 m the plasma jet is almost completely magnetized. The degree of displacement of the magnetic field in the jet is determined by the ion density and the plasma temperature. In I-2 the maximum plasma density is $n_i = 4 \times 10^7$ cm^{-3}. If the weakening of the magnetic field is not large, it follows from the pressure balance condition (1) that the plasma with a such density could weaken the magnetic field only by a few percent, which is really observed in the experiment.

Immediately after the injection begins, a smooth increase in the magnetic field is recorded, which is associated with the propagation of a magnetosonic disturbance in the background plasma at the Alfven velocity. The maximum compression of the magnetic field reaches ~0.5%. The compression at the front is followed by a slight weakening of the magnetic field in the jet (a weak diamagnetic effect).

The lower panel of Figure 6 shows the results of measurements of the quasi-constant electric field along the Y-axis perpendicular to the jet velocity vector and to the magnetic field. Here is also shown the result of calculating the value of the electric field according to the formula $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$, where $\mathbf{V} = L/t$ is the time-of-flight speed, $L = 537$ m is the distance to the plasma generator. From 26 ms E_y of positive polarity associated with the movement of a plasma jet with $\beta < 1$ across the magnetic field is recorded. The experimental and calculated values of the field at this time are almost the same. At the next moment of time, the transverse electric field in the jet is less than the value of VB/c. Plasma depolarization is observed.

In this case, it should be expected that the motion of the plasma jet will be accompanied by the excitation of Alfven waves in the ionospheric plasma, which carry FAC along the magnetic field lines. In the FAC

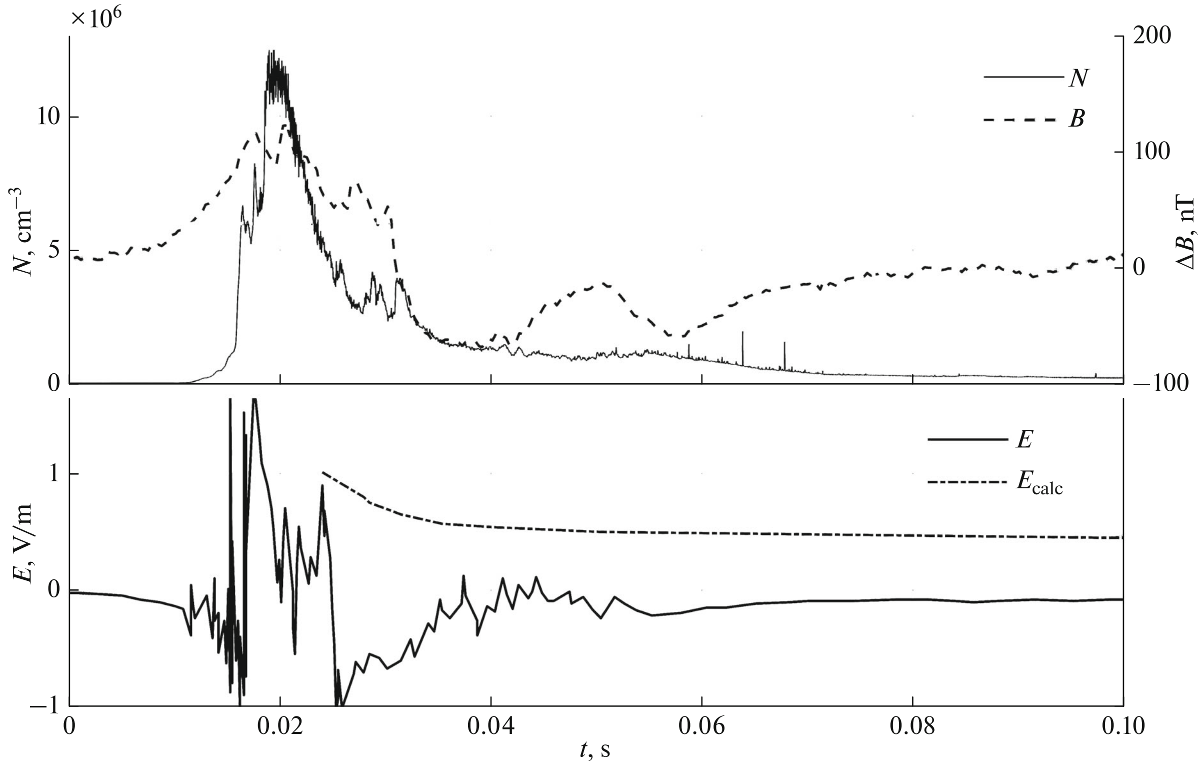

Fig. 6. Results of measurements of the plasma density N, variations of the magnetic field in the jet B, the electric field in the jet E, and the calculated value of the electric field E_{calc} at a distance of 530 m from the plasma generator in the NS I-2 experiment.

layers, the background plasma is entrained into motion in the direction of the plasma flow. The kinetic energy of the flow is transferred to the background plasma, and the plasma jet is slowed down.

In general, FAC can be closed by conduction currents in the collisional background plasma or by polarization currents at the Alfven wave front. At an altitude of 280 km, the ions and electrons of the background plasma are magnetized and FAC closure by conduction currents in the surrounding background plasma does not occur. In this case, the FAC closure can occur in the lower layers of the ionosphere, where the conductivities along and across the magnetic field are compared at an altitude of ~100 km. Then the characteristic propagation time of the Alfven wave is $t_A = 180/V_A = 180$ ms, where $V_A \sim 1000$ km/s is the Alfven velocity. Thus t_A value significantly exceeds the time of observation of the jet on the measuring modules. In this case, the FAC closure could only be performed on the Alfven wave front. However, a weak deceleration of the jet was observed in the experiment. The jet goes a considerable distance away.

A similar "skidding effect" was recorded in the CRRES experiment (Bernhardt, 1992; Delamere, 1996), when several barium injections were performed at altitudes of 400–500 km across the geomagnetic field in daytime conditions. It was found that the plasma cloud travels an unusually long path (up to 100 km) across the magnetic field (Delamere, 2000). According to the authors, the difference between this result and the calculated one is explained by the appearance of electric fields in the FAC layers. This leads to a decrease in the FAC, and, consequently, to a decrease in the efficiency of the energy transfer from the jet to the ionosphere (Borovsky and Bonnel, 2001). The reason for the appearance of magnetic field-aligned electric fields can be the development of instabilities, the inertia of electrons, the appearance of abnormal conductivity.

The weak deceleration efficiency in Injection-2 may also be due to the presence in the plasma stream of a large number of neutrals, which in the process of resonant recharge transmit the kinetic energy of the ionized part of the jet, which is slowed down in a magnetic field by the Ampere force. A similar situation occurs in MHD generators, where the electrical energy is drawn from the neutral gas flow, and a small quantity of charged particles is only an intermediate element that ensures the interaction of the neutral gas with the magnetic field.

The strong depolarization of the jet recorded in the experiment (lower panel Fig. 6) could lead to a deflection of the plasma flow. From the measurements of the Langmuir probes, it can be seen that the dense part of the jet passed 1600 m in the direction of injection.

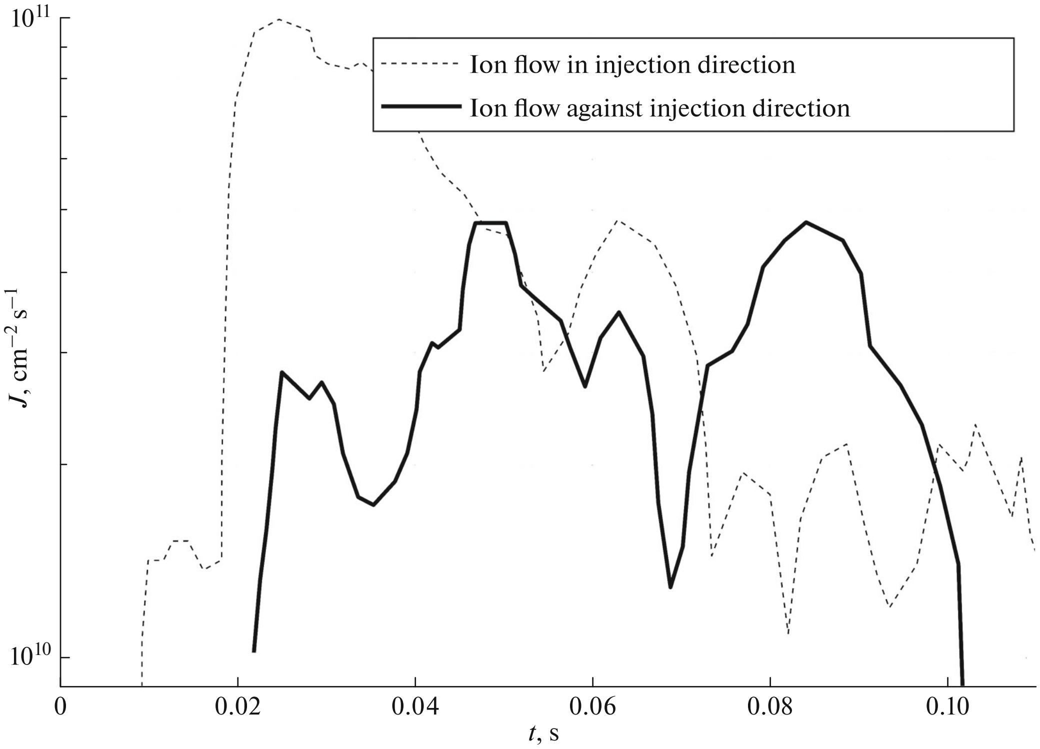

Fig. 7. Experiment NS I-2. Integral flows of ions moving in the direction of injection and in the opposite direction according to the data of the IESA ion analyzer at a distance of 537 m from the plasma generator.

However, in the dense peripheral parts of the jet, effective depolarization could be observed. Figure 7 shows the results of measurements with the IESA analyzer (Lynch et al., 2004), which show the integral ion fluxes that move both in the injection direction and in the opposite direction. There is a periodicity of the reverse flow value of ~20 and ~40 ms. These periods are close to the gyroperiod of the aluminum ion T_{ci} = 35 ms. Starting from 50 ms, the ion fluxes in the forward and reverse directions become comparable, and at 80 ms the ions move mainly in the opposite direction. It is possible that the source of the periodically repeated flow of particles moving in the opposite direction may be the ions of the less dense peripheral parts of the jet, where the depolarization efficiency is quite high. These ions perform a collective Larmor rotation and leave the jet in a spiral trajectory along the magnetic lines of force.

In a paper (Brenning, 1991) devoted to the results of the CRIT experiment, this effect was observed and was called a "barium swarm." In these experiments, as well as in the NS I-2, the component E_y transverse to the velocity vector was found to be less than the value of $E = VB/c$ (Kelley, 1991). As a result, the current in the jet was directed at an angle to the velocity vector. The total Ampere force should slow down the plasma cloud and deflect it from the injection direction. Under the conditions of the CRIT experiments, this led to the collective rotation of the injected particles around the magnetic field lines with the gyro-frequency of the ions.

Analysis of the pitch-angular distribution of electrons in the NS I-1 experiment showed that in channels with an energy of 1581 and 727.5 eV with a trap directed along the magnetic field, bursts of electron flow were registered 1–1.5 seconds after injection (Fig. 8). The reason for their appearance may be the precipitation of particles caused by the propagation in the ionosphere of the MHD perturbation stimulated by the injection of a plasma jet.

A possible confirmation of this version is the result of measurements made by the SPIM slit spectrographs installed on the MSX satellite (Mill et al., 1994) that observed the experiment from a distance of 2500–3000 km. An increase in the intensity of the glow was detected outside the injection zone (Fig. 9). The most intense glow was observed at the wavelengths of 628.7 and 634.5 nm, close to the atomic oxygen line. After 1 second after injection, the brightness of the glow increases by about 3–3.5 times. The glow could be caused by ionization of the background gas by the fluxes of precipitating electrons (Poklad et al., 2018).

DISCUSSION AND CONCLUSIONS

The study of the origin and evolution of plasma flows of various origins and scales in the magnetosphere and the ionosphere is one of the fundamental

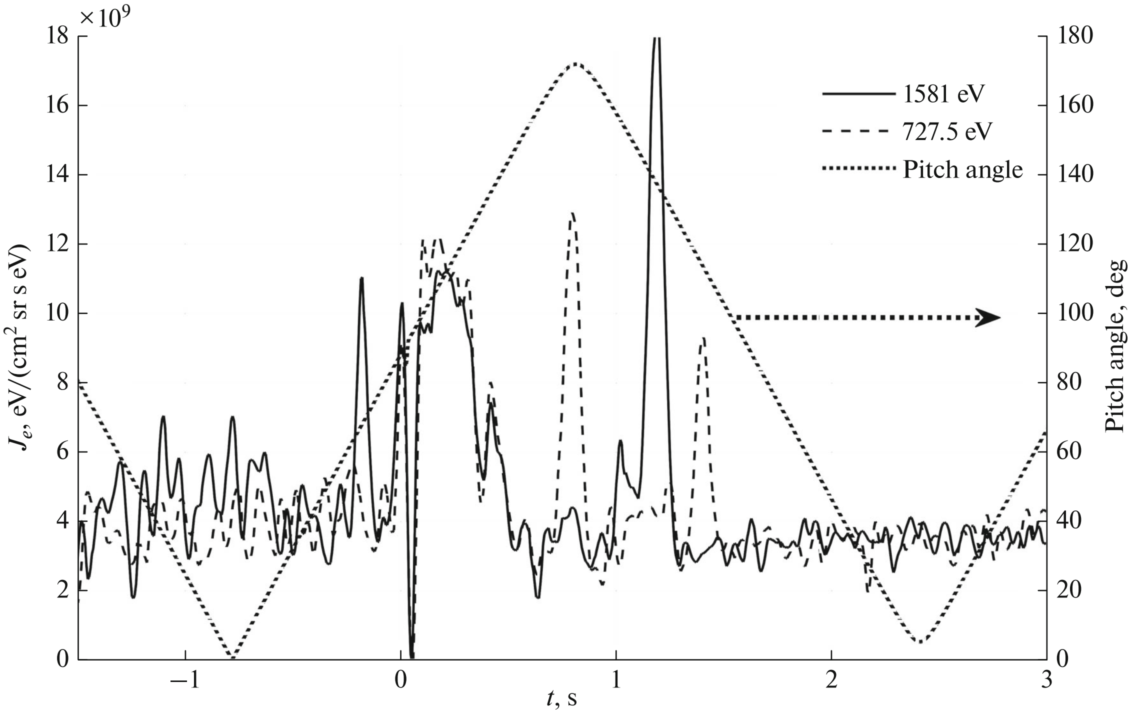

Fig. 8. Electron flow and pitch angle of the trap of the SESA electron analyzer in the NS I-1 experiment. The horizontal axis shows the time relative to the injection moment.

problems of modern geophysics, the study of which in real natural conditions presents significant difficulties. Some progress has been made in studying the electrodynamic and plasma effects accompanying the evolution of PF in the magnetic field under laboratory conditions. At the same time, the natural limitations of adequate scaling of the complex system of plasma propagation in the atmospheric-ionospheric-magnetospheric system is an obstacle to a full-fledged laboratory simulation.

For a number of decades, great hopes were placed on conducting active experiments in the ionosphere and magnetosphere. Indeed, these experiments provided a large amount of important information about the mechanisms of interaction between the plasma and the background medium. The formation and annihilation of a diamagnetic cavity, the generation of electromagnetic and plasma waves, and the generation of electric fields and currents were successfully reproduced and studied in space experiments (Haerendel, 2019). The results of numerous active experiments continue to be the subject of discussion by the scientific community. In September 2017, a scientific conference entitled "Active Experiments in Space: Past, Present, and Future" (Delzanno et al., 2020) was held in Santa Fe, New Mexico, USA. The main purpose of the workshop was to discuss ideas and concepts that could contribute to the development of active space experiments. The participants noted a decrease in interest in such studies and tried to understand its causes. The main ones were the complexity and the increasing of cost of active experiments, their short duration and the relatively small amount of scientific data that can be obtained at the expense of significant resources. However, the participants came to the conclusion that it was advisable to resume the experiments. This requires identifying scientific questions that can only be answered by active experiments, expanding the scope of their results to other fields of knowledge, such as astrophysics, quantum and atmospheric physics, and linking the formulation and application of the results to practical applications.

The original scheme of the North Star experiment made it possible for the first time to carry out complex multipoint measurements of plasma parameters both inside the plasma stream and remotely from the Earth's surface and with the equipment of the MSX satellite located at a distance of about 3000 km from the injection point. The considerable amount of data obtained in the NS experiment and the earlier "Fluxus" experiment on the jet glow, the excitation and ionization of the background gas, its abnormally long glow and the abnormally large size of the luminous region, which significantly exceed the calculated values, are discussed in detail in a number of papers (Erlandson et al., 1999, 2002).

The analysis of the experimental results showed that its scheme, parameters of explosive plasma generators, and diagnostic equipment made it possible to

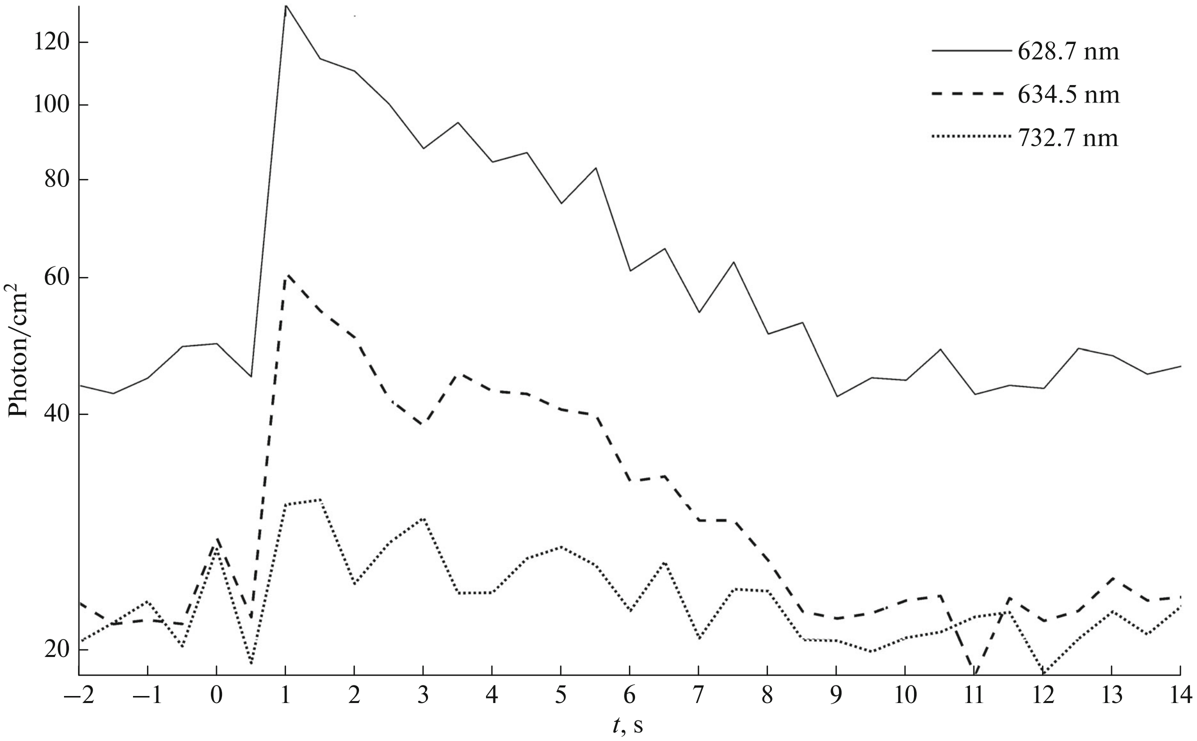

Fig. 9. The average brightness of the glow outside the injection zone in the NS I-1 experiment according to the SPIM spectrograph of the MSX satellite. The horizontal axis shows the time relative to the injection moment.

reproduce in a real geophysical environment the most important effects of the interaction of natural ionospheric plasma flows with the background environment and the geomagnetic field, which continue to be the subject of active study. The conditions for the formation of a diamagnetic cavity and the dependence of this process on the flow parameters, the generation of electric fields and currents, plasma deceleration, the generation of MHD perturbations in front of the jet, the diffusion of the magnetic field into the plasma, and the formation of a boundary layer were studied in detail. The analysis of the measured parameters of electric and magnetic fields, changes in the plasma density, energy, and pitch-angular distribution of ions and electrons shows a fairly consistent picture of the interaction of PF and the magnetic field.

Among the actual problems not implemented in the experiment, we can note the lack of direct measurements of MHD waves and FAC propagating from the plasma jet, the precipitation of particles and their influence on the effects in the environment surrounding the plasma jet. Measurements of electric fields in plasma show that disturbances along the magnetic field in the form of an Alfven wave should be generated with a high probability, causing corresponding effects in the surrounding gas in the form of entrainment, heating, additional ionization and acceleration of charged particles in the case of field-aligned electric fields in violation of the equipotential of magnetic field lines, the appearance of double layers or areas of anomalous resistance as a result of the development of hydrodynamic or plasma instabilities. At I-1, these phenomena could occur at times exceeding the measurement time. At I-2, the plasma jet was magnetized almost from the very beginning, so the generation of FAC seems obvious. But their magnitude, configuration, and evolution are not measured.

The same can be said about the afterglow in the lines of atomic oxygen and the electron fluxes registered in the experiment along the magnetic field. The mechanism of excitation of the background gas due to the wave-particle interaction may well be realized under experimental conditions. In future studies, it would be desirable to be able to directly register the relevant energy transfer agents.

In (Delzanno et al., 2020), breakthrough technologies that can take rocket experiments to a new level are discussed, and their effective integration with the actively developing technology of nanosatellites (microsatellites) or cubesats is proposed. The possibility of using small-sized diagnostic devices equipped with particle analyzers, magnetometers and Rogovsky belts installed at a distance from the plasma jet both on the path of its propagation and along the geomagnetic field lines at a distance of about 1 km would allow us to solve this problem.

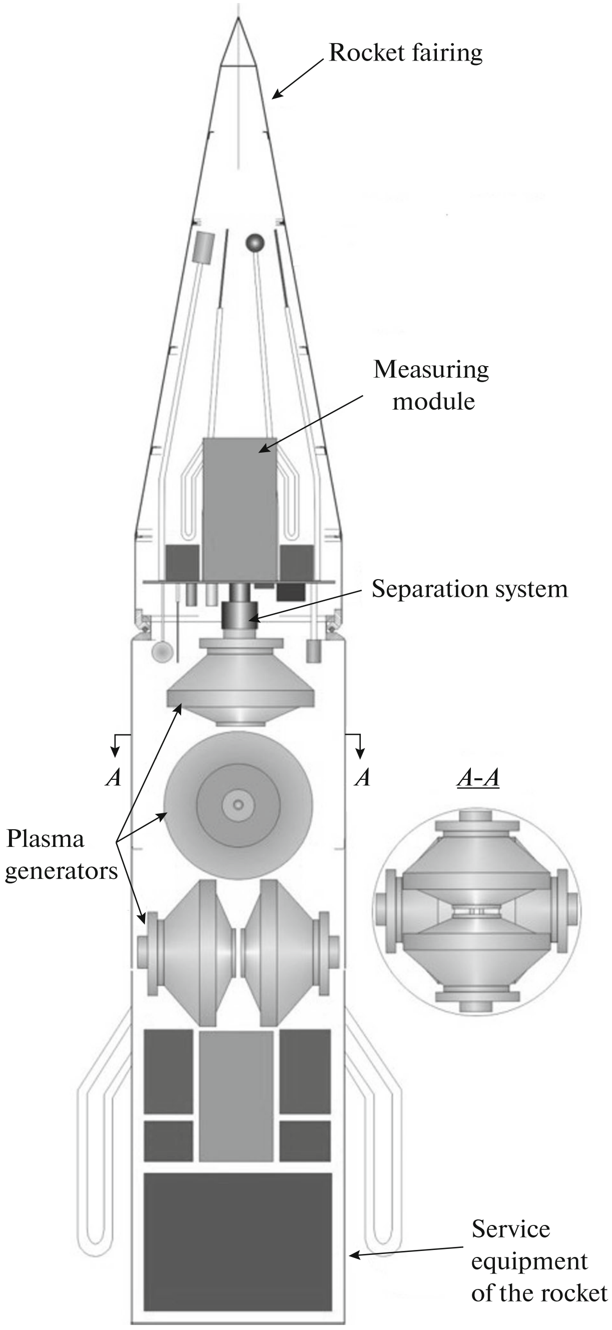

Fig. 10. A variant of the layout of the rocket head with an ensemble of explosive plasma generators.

Many questions remain about the dominant mechanisms of interaction between high-velocity plasma and an air cloud in the NS I-1 experiment. Gasdynamic estimates show that after the shock wave reaches the boundary of the air cloud, the gas must accelerate to values exceeding the registered jet velocity. The divergence angle of the air jet is about twice the divergence angle of the aluminum jet, and although the latter retains its shape, its maximum velocity decreases. From the measurement data on the axis of the jet, it can be seen that after its exit from the cloud, the high-speed part of the jet is eaten out. The expansion of the high-speed part of the jet at a significantly wider angle in the presence of an air cloud than in the case of injection into a vacuum must be taken into account when comparing the two injections in the NS experiment.

The success of our experiments allows to consider the development and/or expansion of future research scenarios, taking into account the capabilities already implemented in NS. From the point of view of improving or changing the characteristics of the injected plasma flow, a scheme for using a set of plasma generators is considered, which allows increasing the energy and mass of plasma formation by creating counter-plasma flows of different composition, which can be initiated simultaneously or with a given delay, depending on the tasks of the experiment and a given radiation spectrum (UV, X-ray, super-rigid X-ray radiation) (Fig. 10).

It is hoped that the progress in the development of rocket and space technology, the development of new diagnostic methods and devices will serve as an incentive and a basis for conducting new active experiments in space.

FUNDING

This work was supported by the Ministry of Science and Higher Education of the Russian Federation, project no. AAAA-A17-117112350014-8.

REFERENCES

Active Experiments in Space: Past, Present, and Future, Delzanno, G.L., Borovsky, J.E., and Mishin, E.V., Eds., Lausanne: Frontiers Media SA, 2020. https://doi.org/10.3389/978-2-88963-659-4

Adushkin, V.V., Zetser, Yu.I., Kiselev, Yu.N., Nemtchinov, I.V., and Khristoforov, B.D., Active geophysical rocket experiments with injection of a high-velocity plasma jet in the ionosphere, *Dokl. Akad. Nauk*, 1993, vol. 331, no. 4, pp. 486–489.

Adushkin, V.V., Zetser, Yu.I., Zotov, N.I., Kiselev, Yu.N., Khristoforov, B.D., Yur'ev, V.L., and Poklad, Yu.V., RF Patent for Invention no. 2144685, 2000.

Alfven, H., *Cosmic Plasma*, Dordrecht: Springer, 1981.

Angelopoulos, V., Baumjohann, W., Kennel, C., Coronti, F.V., Kivelson, M.G., Pellat, R., Walker, R., Luehr, H., and Paschmann, G., Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res.*, 1992, vol. 97, no. A4, pp. 4027–4040.

Baumjohann, W., Paschmann, G., and Lühr, H., Characteristics of high-speed ion flows in the plasma sheet, *J. Geophys. Res.*, 1990, vol. 95, no. A4, pp. 3801–3809.

Bernhardt, P.A., Probing the magnetosphere using chemical releases from the combined release and radiation effects satellite, *Phys. Fluids*, 1992, vol. B4, no. 7, pp. 2249–2256.

Bernhardt, P.A., Roussel-Dupre, R.A., Pongratz, M.B., Haerendel, G., Valenzuela, A., Gurnett, D. A., and Anderson, R.R., Observation and theory of the AMPTE magnetotail barium releases, *J. Geophys. Res.*, 1987, vol. 92, no. A6, pp. 5777–5794.

Borovsky, J.E. and Bonnell, J., The dc electrical coupling of flow vortices and flow channels in the magnetosphere to the resistive ionosphere, *J. Geophys. Res.*, 2001, vol. 106, no. A12, pp. 28967–28994.

Brenning, N., Kelley, M.C., Providakes, J., Stenbaek-Nielsen, H.C. and Swenson, C., Barium swarm: An ionospheric alternating current generator in CRIT-I, *J. Geophys. Res.*, 1991,vol. 96, no. A6, pp. 9735–9743.

Delamere, P.A., Stenbaek-Nielsen, H.C., Hampton, D.L., and Wescott, E.M., Optical observation of the early ($t < 5$ s) ion dynamics of the CRRES G1, G9 and G11A releases, *J. Geophys. Res.*, 1996, vol. 101, no. A8, pp. 17243–17257.

Delamere, P.A., Stenbaek-Nielsen, H.C., Swift, D.W. and Otto, A., Momentum transfer in the combined release and radiation effects satellite plasma injection experiments: The role of parallel electric fields, *Phys. Plasmas*, 2000, vol. 7, no. 9, pp. 3771–3780.

Delamere, P., Stenbaek-Nielsen, H., Pfaff, R., Erlandson, R., Meng, C., Zetzer, J., et al., Dynamics of the Active Plasma Experiment North Star artificial plasma jet, *J. Spacecr. Rockets*, 2004, vol. 41, no. 4, pp. 503–508.

Dimonte, G. and Wiley, L.G., Dynamics of exploding plasmas in a magnetic field, *Phys. Rev. Lett.*, 1991, vol. 67, no. 13, pp. 1755–1758.

Dungey, J.W., *Cosmic Electrodynamics*, Cambridge: Cambridge Univ. Press, 1958.

Erlandson, B., Meng, C.-I., Zetzer, J., Kiselev, Y., Gavrilov, B., Stenbaek-Nielsen, H., Lynch, K., Pfaff, R., Swaminathan, P., Kumar, C.K., Dorga, V.K., Stoyanov, B.J., Delamere, P.A., Bounds, S.R., and Gatsonis, N.A., The APEX North Star experiment: observation of the high-speed plasma jets injected perpendicular to the magnetic fields, *Adv. Space Res.*, 2002, vol. 29, pp. 1317–1326.

Erlandson, R.E., Swaminathan, P.K., Meng, C.-I., Stoyanov, B.J., Zetzer, J.I., Gavrilov, B.G., Kiselev, Yu.N. and Romanovsky, Yu.A., Observation of auroral emissions induced by artificial plasma jets, *Geophys. Res. Lett.*, 1999, vol. 26, no. 11, pp. 1553–1556.

Fuselier, S.A., Mende, S.B., Geller, S.P., Miller, M., Hoffman, R.A., Wygant, J.R., Pongratz, M., Meredith, N.P., and Anderson, R.R., Dynamics of the CRRES barium releases in the magnetosphere, *J. Geophys. Res.*, 1994, vol. 99, no. A9, pp. 17379–17390.

Gavrilov, B.G., Zetser, Yu.I., Podgornyi, A.I., and Podgornyi, I.M., Electrodynamical deceleration of the plasma jet at its injection into the magnetosphere and the ionosphere heating, *Dokl. Akad. Nauk*, 1994, vol. 336, no. 5, pp. 684–687.

Gavrilov, B.G., Podgorny, A.I., Podgorny, I.M., and Zetzer, J.Y., The investigation of the field-aligned current generation during injection of plasma jet into the magnetosphere, *Geomagn. Aeron.*, 1995, vol. 34, no. 5, pp. 600–604.

Gavrilov, B.G., Kiselev, Y.N., Podgorny, I.M., Sobyanin, D.B., Zetzer, J.I., Erlandson, R.E., and Meng, C.-I., Dynamics of a high energy plasma jet in space: in situ experiment and laboratory simulation, *Adv. Space Res.*, 1998, vol. 21, no. 5, pp. 773–776.

Gavrilov, B.G., Zetzer, J.I., Podgorny, I.M., Sobyanin, D.B., Meng, C.-I., Erlandson, R.E., Stenbaek-Nielsen, H.C., Pfaff, R.F., and Lynch, K.A., Plasma jet motion across the geomagnetic field in the "North Star" active geophysical experiment, *Cosmic Res.*, 2003, vol. 41, no. 1, pp. 28–38.

Gavrilov, B.G., Podgorny, I.M., Sobyanin, D.B., Zetzer, J.I., Erlandson, R.E., Meng, C.I., Pfaff, R.F., and Lynch, K.A., North Star plasma-jet experiment particles and electric and magnetic field measurements, *J. Spacecr. Rockets*, 2004, vol. 41, no. 4, pp. 490–495.

Haerendel, G., Experiments with plasmas artificially injected into near-Earth space, *Front. Astron. Space Sci.*, 2019, vol. 6, Article 29.
https://doi.org/10.3389/fspas.2019.00029

Iijima, T. and Potemra, T.A., The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad, *J. Geophys. Res.*, 1976, vol. 81, no. A13, pp. 2165–2174.

Kamide, Y. and Baumjohann, W., *Magnetosphere-Ionosphere Coupling*, Ser. Physics and Chemistry in Space Planetology, vol. 23, Berlin: Springer, 1993.

Kelley, M.C., Swenson, C.M., Brenning, N., and Pfaff, R., Electric and magnetic field measurements inside a high-velocity neutral beam undergoing ionization, *J. Geophys. Res.*, 1991, vol. 96, no. A6, pp. 9703–9718.

Lynch, K.A., Torbert, R.B., Chutter, M., Erlandson, R.E., Meng, C.I., Zetzer, J.I., Gavrilov, B.G., and Kiselev, Y., Active plasma experiment: North Star particle data, *J. Spacecr. Rockets*, 2004, vol. 41, no. 4, pp. 496–502.

Lysak, R.L., Auroral electrodynamics with current and voltage generators, *J. Geophys. Res.*, 1985, vol. 90, no. A5, pp. 4178–4190.

Mill, J.D., O'Neil, R.R., Prace, S., et al., Midcourse space experiment: introduction to the spacecraft, instruments, and scientific objectives, *J. Spacecr. Rockets*, 1994, vol. 31, no. 5, pp. 900–907.

Petrukovich, A.A., Baumjohann, W., Nakamura, R., Schödel, R., and Mukai, T., Are earthward bursty bulk flows convective or field-aligned?, *J. Geophys. Res.*, 2001, vol. 106, no. A10, pp. 21211–21215.

Pfaff, R.F., Freudenreich, H.T., Bounds, S., Delamere, P.A., Erlandson, R.E., Meng, C.I., Zetzer, J.I., and Gavrilov, B.G., Electric field, magnetic field, and density measurements on the active plasma experiment sounding rocket, *J. Spacecr. Rockets*, 2004, vol. 41, no. 4, pp. 521–532.

Poklad, Yu.V., Gavrilov, B.G., Zetzer, J.I., et al., Trigger effect of the afterglow background medium after injection of the high speed plasma jet in the Fluxus and North Star experiments, *Proc. 24th Int. Symp. on Atmospheric and Ocean Optics: Atmospheric Physics*; Tomsk, 2018, vol. 10833, Paper ID 108339H.
https://doi.org/10.1117/12.2504059

Raizer, Yu.P., The deceleration and energy conversions of a plasma expanding in vacuum in the presence of a magnetic field, *Prikl. Mekh. Tekh. Fiz.*, 1963, vol. 4, no. 6, pp. 19–28. Transl. as NASA Tech. Tramnsl. No. TTF-239, 1964.

Scholer, M., On the motion of artificial ion clouds in the magnetosphere, *Planet. Space Sci.*, 1970, vol. 18, pp. 977–1004.

Sergeev, V.A., Sauvaud, J.-A., Popescu, D., Kovrazhkin, R.A., Liou, K., Newell, P.T., Brittnacher, M., Parks, G., Nakamura, R., Mukai, T., and Reeves., G.D., Multiple-spacecraft observation of a narrow transient plasma jet in the Earth's plasma sheet, *Geophys. Res. Lett.*, 2000, vol. 27, no. 6, P. 851–854.

Shiokawa, K., Baumjohann, W., and Haerendel, G., Braking of high-speed flows in the near-Earth tail, *Geophys. Res. Lett.*, 1997, vol. 24, no. 10, pp. 1179–1182.

Sobyanin, D.B., Gavrilov, B.G., and Podgorny, I.M., Laboratory investigation of plasma jet interaction with transverse magnetic field, *Adv. Space Res.*, 2002, vol. 29, no. 9, pp. 1345–1349.

Swenson, C.M., Kelley, M.C., Brenning, N., Torbert, R., Primdahl, F., and Baker, K.D., CRIT II electric, magnetic, and density observations in an ionizing neutral jet, *Adv. Space Res.*, 1992, vol. 12, no. 12, pp. 65–90.

Valenzuela, A., Haerendel, G., Föppl, H., Melzner, F., Neuss, H., Rieger, E., Stöcker, J., Bauer, O., Höfner, H., and Loidl, J., The AMPTE artificial comet experiments, *Nature*, 1986, vol. 320, no. 6064, pp. 700–703.

Zetzer, J.I., Kozlov, S.I., Rybakov, V.A., Ponomarenko, A.V., Smirnova, N.V., Romanovsky, Yu.A., Meng, C.-I., Erlandson, R., and Stoyanov, B., Airglow in the visible and infrared spectral ranges of the disturbed upper atmosphere under conditions of high-velocity plasma jet injection: I. Experimental data, *Cosmic Res.*, 2002, vol. 40, no. 3, pp. 233–240.