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Negative Ions in Space Exploration

When space vehicles enter the dense layers of the atmosphere at orbital velocity the plasma which is formed in the double electric layer results in radio communication interruptions occurring during the active phase of flight at altitudes from 80 to 20 km, and when space vehicles enter the atmosphere at the escape velocity the plasma of the double electric layer not only causes radio communication interruptions, but significantly increases the energy flow leading to the explosive mechanism of burning of the heat-shielding coating. When space vehicles fly at high altitudes, the emission of negative electrons from their surfaces induce a positive potential of several kilovolts. This potential impacts the electronic equipment of the satellite significantly. When space vehicles fly at the altitudes from 100 km to 500 km, an intense glow around the front hemispheres of the space vehicles occurs (Gretchikhin Effect) with its maximum at the altitude from 110 to 140 km. At the moment of transition from the illuminated zone to the zone of the Earth's shadow the intensity of the glow increases sharply.

Introduction.

Intensive development of rocket technologies began immediately after World War II. There were developed geophysical rockets to explore outer space. The results of the measurements performed in the vicinity of the surface of one of such rockets showed that only negative ions with masses of 46, 32, 29, 22, 16 atomic mass units were present [1]. Their percentages are accordingly: 96.5; 1.6; 0.2; 1.0; 0.7. Positive ions of nitrogen were present in the illuminated zone. Ions with mass numbers of 46, 32 and 16 should be identified as NO_2^-, O_2^- and O^-. Mass numbers 29 and 22 correspond to the products of gasification and, probably, sodium. All molecules and atoms have a noticeable electron affinity. This publication was followed by intensive studies of negative ions. The results of theoretical and experimental studies carried out in that area are reflected in H. Massey's monograph [2]. Further on, the interest towards negative ions, reflected in open sources, decreased substantially.

When the intensive exploration of the space began, the interest to negative ions reappeared. The following problems were faced: 1. How to ensure uninterrupted radio communications with the descent vehicles of artificial Earth satellites (AESs). 2. How to protect the descent vehicles when entering the dense layers of the atmosphere at the escape velocity. 3. Why on-board electronics of artificial Earth satellites fails at high altitudes. 4. What processes occur at the surface of the spacecraft flying at high altitudes in the free-molecular flow regime. All these problems required their immediate resolution. Now let us consider these problems and find out the role negative ions played.

Ensuring uninterrupted radio communications with the descent vehicles at orbit velocity.

First launches of geophysical rockets of R-1, R-2, R-5 types made it possible to find out radio communications were interrupted during the most important phase of rockets descend: from the altitude of 80 km to 20 km one. However as early as in 1959 the preparations for launching man into space began. Meanwhile, the main obstacle in the implementation of the launch was the lack of the reliable radio communications during a particularly dangerous part of the flight where powerful shock waves occur, and radio communication is interrupted. Theoretical calculations of the impact made by aerodynamic heat fluxes showed that communications in the meter range of radio waves should not be broken. The cause of the communication interruptions remained unclear. It was dangerous to launch man into space. The studies of destruction of heat-shielding coating consisting of phenolic graphite began.

When the satellite descends in the active phase of the flight, the air behind the shock wave is heated to a temperature above 1000 K with a maximum amounting up to 3500 K. Under such high temperatures, the heat-shielding coating in the form of phenolic graphite is rapidly destroyed. The phenomenon of ablation occurs. The products of destruction contain predominantly nitrogen dioxide and triatomic carbon molecules, which possess electron affinity of 2.42 and 2.5 eV, respectively [3] and therefore with a certain probability leave the satellite surface in the form of negative ions. As a result, a double electric layer appears at the surface of the satellite and plasma with high concentration of charged particles corresponding to the arc discharge is realized within the layer. Figure 1 shows the results of the calculation of charged particles concentration for the descent vehicle in the form of a ball with the radius of 1 m [4]. In case of radio communication in

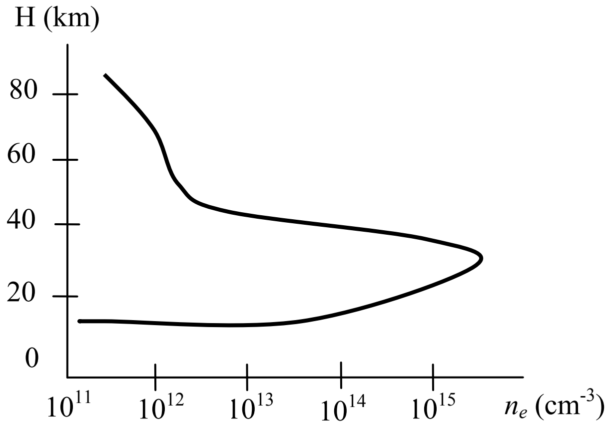

Figure 1. Concentration of electrons of the double electric layer as a function of the altitude of descending satellite

decimeter wavelength range, the communication completely fails starting from the altitude of 80 km. There are two possibilities to ensure uninterrupted radio communications in the decimeter and centimeter ranges: either to introduce a substance with a low ionization energy (alkali metals) into the double electric layer; in this case plasma temperature will sharply decrease and negative ions ionization will cease, or to apply magnetic field to the double layer plasma. The first option is simpler and therefore was applied, however without any specific substantiation.

When an artificial satellite of the Earth enters the dense layers of the atmosphere at the altitude of 50 km, the flight speed amounts to ~ 6 km/s while radio communications with the satellite are carried out at the frequency f = 640 MHz, for which the critical concentration of charged particles amounts to $5{,}076 \cdot 10^{15}$ m^{-3}. To ensure complete signal passage through the plasma, the concentration of charged particles in the double electrical layer should be an order of magnitude smaller, i.e., $5.077 \cdot 10^{-14}$ m^{-3}. In reality, the concentration of charged particles within the double electric layer at the altitude of 50 km amounts to $n_e \approx 2 \cdot 10^{17}$ m^{-3} at the plasma temperature of 3100 K. Plasma frequency is equal to $f_0 \cong 4 \cdot 10^9$ Hz. Therefore, the frequency of $6{,}4 \cdot 10^8$ Hz will be completely reflected form plasma with concentration of $n_e \approx 2 \cdot 10^{17}$ m^{-3}. To provide radio communications, it is necessary to ensure plasma blooming, which practically was realized by introducing a liquid-crystalline coolant into the combustion zone.

Figure 2 diagrammatically shows the injection of liquid crystal coolant into the front hemisphere of the descent vehicle of the AES. Under continuous flow in the front hemisphere of the AES 1, travelling with supersonic velocity 4, the shock wave 2 arises. The direct jump in the compression features the shape of a circle with the diameter equal to the size of the descent vehicle. The shift of the shock wave relative to the AES amounts to ~17 cm. During the injection of the liquid metal

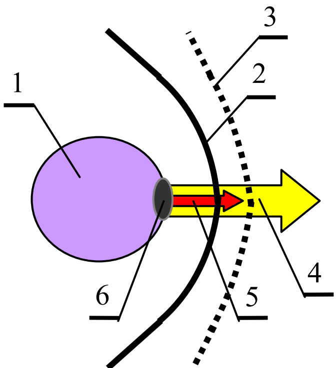

Figure 2. General diagram of the injection of liquid crystal coolant into the front hemisphere: 1 – AES; 2 – shock wave before the coolant has been injected; 3 - shock wave after the coolant has been injected; 4 – velocity of the AES; 5 – coolant injection speed; 6 – opening for coolant injection

coolant, the shock wave is straightened. The shift of the shock wave relative to the AES rises somewhat while the Mach cone increases noticeably. The temperature behind the shock wave drops due to an increase in the gas density and due to endothermic chemical reactions. This is how the active thermal protection of supersonic aircraft works. The decrease in temperature due to an increase in the gas density can be neglected as normally only a small portion of foreign matter is injected, this is also leads to a relatively small increase in the shift of the shock wave relative to the body streamlined. Therefore, gas cooling behind the shock wave under active heat protection occurs mainly due to the endothermic chemical reactions. The alloy of sodium and potassium is used as a liquid-metal coolant in aviation. The mass of potassium is 77.2% and the mass of sodium is 22.8%. Such alloy features a melting point of minus 12.80^{0}C and possesses high heat transfer coefficient. What determines such qualities?

In the liquid state at the melting point, the bonds between the cluster formations break while at the boiling point the cluster formations break up into separate molecules. In the solid state, sodium and potassium form a body-centered structure. Such structure is formed by diatomic molecules. Standard enthalpy of atomization of sodium at the temperature of 250 ° C amounts to 91.7 kJ/mol while for potassium the value equals to 90.3 kJ/mol. At the temperature of 298 K and even at the temperature of 3100 K, the disintegration of diatomic molecules Na_2 and K_2, possessing dissociation energy of 0.75 eV and 0.5 eV, respectively, into individual atoms is very unlikely. In the process of the disintegration of a body-centered cluster, it is necessary to break 8 pairs of bonds between diatomic molecules. Taking this fact into account, we find that the breaking of the bonds between the molecules in clusters of sodium and potassium amount to 0.119 eV and 0.111 eV, and on the average, about 0.059 eV per one molecule of potassium or sodium.

At the temperature of 3100 K the ionization of negative ions of nitrogen dioxide and triatomic carbon molecules occurs to decrease the degree of ionization by the value of $\eta = 5{,}076 \cdot 10^{14} / 2 \cdot 10^{17} = 2{,}54 \cdot 10^{-3}$. The temperature at which the degree of ionization decreases by 2,54·10^{-3} shall be determined from the Saha formula:

$$\frac{n_e n_i}{n_a} = c' T^{3/2} \exp\left(-\frac{EA}{k_B T} \right), \tag{1}$$

where $\lg c' = 15{,}38$, EA = 2,5 eV, k_B is Boltzmann constant, n_e. n_i, n_a: the concentrations of electrons, ions, and atoms, correspondingly.

In accordance with (1) the decrease in the degree of ionization of the negative ions of triatomic carbon molecules down to 2.54·10^{-3} 2.54 · 10^{-3} will occur at the temperature of 1440 K. This temperature exceeds the boiling point of sodium and potassium. Therefore, clusters of sodium and potassium will not be formed. The air density behind the front of the shock wave at the altitude of 50 km:

$$\rho = \rho_\infty \left(\frac{\gamma - 1}{\gamma + 1} + \frac{2}{\gamma + 1} \frac{1}{M^2} \right)^{-1} \cong 1{,}46 \cdot 10^{-2} \text{ кг/м}^3. \tag{2}$$

The number of particles per unit volume will amount to ~ $3{,}032\cdot10^{23}$ $1/m^3$. Each particle of the air reduces its kinetic energy by the amount of $k_B T_2 - k_B T_1 \approx 0{,}143$ eV, and the number of sodium or potassium molecules that will provide such decrease in energy is equal to $N = 0{,}143/0{,}059 \approx 2{,}424$. Then the mass of the coolant, which will ensure the decrease in temperature down to 1440 K will be as follows:

$$\Delta m = \rho N \overline{M} \pi R^2 \Delta \approx 0.0463 \text{ kg}, \quad (3)$$

i.e. just 46.3 grams of liquid crystal coolant.

At the first cosmic velocity, the emission of negative ions from the surface of the heat protection due to catalytic reactions is not intensive enough. Therefore, the energy flux transferred by free electrons due to the ionization of negative ions can be neglected however when the vehicle travels with the escape velocity this flux should not be neglected.

Combustion of the heat-shielding coating of the descend vehicle travelling at the escape velocity.

When arranging flights to other planets, the natural moon of the Earth is of special interest as an intermediate station. Since the Moon at all times faces the Earth with its one side while the far side is not seen, it became necessary to fly around the Moon, to take pictures of the far side of the Moon and to create a map for that side. In this case, upon returning to Earth, the descent vehicle must enter the atmosphere at the escape velocity. Therefore, the heat-shielding coating should burn more intensively. Engineers faced the problem how to keep safe the descend vehicle. The temperature of the shock wave is quite high. Intensive radiant and convective heat exchange are realized; based on these processes it was possible to determine the thickness of the coating that burns out. It appeared the thickness was equal to ~ 2 m. The result was shocking. And here negative ions came to the rescue. Ionization of negative ions creates an intense flow of electrons to the surface of the heat-shielding coating and together with the radiant and convective heat flow creates such a resultant flow that a skin-layer explosion occurs and heat ceases to enter the surface of the spacecraft. This situation was simulated in the laboratory. Figure 3 shows, as

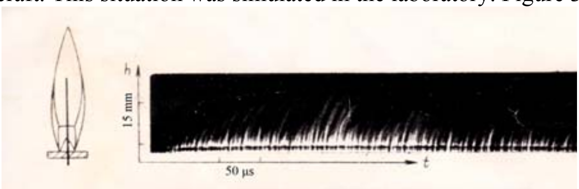

Figure 3**.** Slit scan photo of copper plate exposed to the plasma flux created by concentrated laser radiation ($5\cdot10^7$ W/cm^2)

an example, slit scan photo of plasma torch under the action of laser radiation with the energy flux approximately equal to the aerodynamic energy flux from the shock wave.

Taking into account the experimental data, specific calculations showed that the heat shield of AES travelling at the escape velocity should burn less than that on of the AES travelling with the orbital velocity. These results were reported to Sergei

Korolev and he, at his own peril, decided to make flight around the Moon with further descending at the escape velocity and to use the same heat-shielding coating, with the thickness of 5 cm, that was used previously for spaceships travelling with the orbital velocity. What a surprise it was when it appeared that the thickness of the heat-shield burnt-out during the descent of the vehicle at the escape velocity was only ~ 2 cm while that one of the vehicle descending at orbital velocity amounted to ~ 3 cm. Consequently, combustion of the heat-shielding material at the escape velocity is not continuous but occurs as separate explosive pulses with the frequency of ~ 250 kHz [5,6]. It is negative ions that are responsible for this mechanism of destruction.

Electrification of artificial Earth satellites travelling at high altitudes.

In the late sixties and early seventies, the need arose to detect the launches of ballistic missiles. In 1963-1965 the Institute of Physics of the Academy of Sciences of the BSSR carried out the analysis of main concepts to be used to develop a missile early warning system. In 1966 intensive works related to the development of Ballistic Missile Early Warning System started. State Optical Institute was approved as a lead agency. In 1975 the system was manufactured and space tests began. As soon as the satellites reached the apogee (~ 1500 km) they stopped working. All electronics went out of order. It was urgent to find out the reason.

It turned out that oxygen atoms are adsorbed on the surface of the spacecrafts travelling at high altitudes. These oxygen atoms featuring considerable electron affinity exist in the form of negative ions. Under the action of oncoming flow of nitrogen and oxygen atoms the adsorbed oxygen atoms leave the surface in the form of negative ions. As this takes place, a positive potential is induced on the surface of the satellite. Specific estimates gave a value of ~ 1.5 kV for flights at the altitude of 1500 km. Zero wire of all electronics on-board units is connected to the body of the vehicle and so all electronics got burned through this wire.

Earlier our team was engaged in the investigations of the electrization of aircrafts and rockets. Appropriate electrostatic sensors were developed and measurements were made in the airplanes and the rockets. Therefore, it wasn't any trouble for us to adjust the potential on the zero wire using electrostatic sensors. The problem was solved and the system is working normally now.

U.S. followed us non-stop. Their intelligence service worked well. Whenever we solved a problem, they knew every detail three days later.

A special drama arose around the "Gretchikhin Effect". The effect was predicted in 1969 and was reported in The First Belarusian Space Congress in 2003 [4,7]. Now let us consider the effect in more detail.

Interaction of the spacecraft travelling at high altitude with the environment in the free-molecular flow regime.

So, in 1969, the phenomenon of emission of negative oxygen ions with the formation of a double electric layer was predicted. An intensive violet-blue glow is formed within the forward hemisphere around the satellite travelling at altitudes of up to 500 km with its maximum at the altitude of 110-140 km, mainly in the shadow of the Earth. In 1971, during the emergency descent of the Soyuz-10 spacecraft in the shadow of the Earth, the cosmonauts visually observed this glow.

Based on theoretical calculations of the thickness of the double electric layer at different altitudes, the electron concentration and the energy distribution function, the nonequilibrium radiation of this layer was calculated in different spectral lines and molecular bands of nitrogen and oxygen. Figure 4 shows the results of the calculations for the ball of radius 1 m travelling with velocity of 7.5 km/s. The glow of the double electrical layer at flight altitudes below 180 km is much greater than day airglow and even polar lights. At the flight altitude of ~ 120 km, the nonequilibrium glow is comparable to the magnitude of solar radiation within the range of 400-500 nm (~ 9.6 W/m^{2}sr). The glow varies according to the cosine law depending on the angle of attack. The maximum energy value of the nonequilibrium glow corresponds to the flight altitude of ~ 110 km both in the shadow of the Earth and in the illuminated zone. In the shadow zone of the Earth, the Meinel bands and the bands of the first negative system of hydrogen give a clearly pronounced maximum at the altitude of 120 ... 140 km and have maximum energy of radiation.

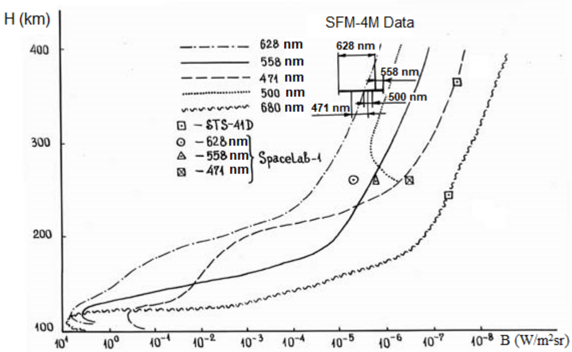

Figure 4. Calculations of altitude curves of the non-equilibrium glow brightness in comparison to the experimental data

In accordance with the predictions of the theory, the measurements were carried out on-board of the long-term space station Salyut-4 with specially designed SFM-4M photometric equipment. At the flight altitude of 350 km, there was detected a luminescence corresponding in brightness to that of the theoretical calculations in the spectral lines of oxygen, nitrogen, and in the molecular nitrogen band. A cosine distribution of the luminescence along the angle of attack was obtained, as predicted by the theory.

Similar results were obtained in the U.S.A. at the spaceships Shuttle, STS-41 и «Spacelab-1» [8,9] ten years later. The results of these measurements are also shown in figure 4. Explanation of the observed frontal glow by chemiluminescence [9, 10] or by discharge model of Papadopoulos [11] does not stand up to scrutiny.

It is necessary to note one more phenomenon caused by the interaction between a solid body with particles of near-Earth space with the participation of negative ions. Under conditions of dynamic equilibrium, the flow of electrons in the environment is partially compensated by the flow of negative ions that escape into surrounding space. Due to the chemical reactions of ionization of negative ions, epithermal electrons with the energies within the range 0.4 ... 3.6 eV are produced. These electrons lead to the effective excitation of the energy levels of atoms and molecules whose spontaneous emission for forbidden oxygen lines is significantly delayed. Therefore, at a certain distance from the spacecraft, there should appear a pink-red halo and the spacecraft trail must also have the same color. The pink-red halo was actually detected with the maximum at the distance of ~ 1 *м* from the spaceship [11].

Thus, the theoretical model of the interaction of a solid body with near-earth space in the free-molecular flow regime in comparison to the experimental data, has been fully confirmed according to the following parameters and functions under investigation: radiation energy, spectral composition, dependences on oxygen concentrations in the environment, altitude curves of the non-equilibrium glow brightness, brightness distribution around the aircrafts, influence of the surfaces on the magnitude of the radiation brightness, energy distribution of electrons, and the direct proof of the presence of negative ions near the aircraft surfaces.

Conclusions.

The atoms featuring considerable electron affinity, in the process of physical and chemical adsorption on the surface of a solid body, exist in the form of negative ions with a certain probability. The emission of negative ions from the surface of the solid body occurs due to temperature evaporation, under the influence of external flow of the particles of the ambient atmosphere, or due to surface catalysis. The emission of negative ions from the surface of the solid body leads to the formation of a double electric layer very close to the surface. As this takes place, the surface of the solid acquires a high positive electric potential. The electron gas in a double electric layer is essentially nonequilibrium. The results are as follows:

1. When space vehicles enter the dense layers of the atmosphere at orbital velocity, the plasma which is formed in the double electric layer causes complete failure of radio communications during the active phase of flight at altitudes from 80 to 20 km.
2. When space vehicles enter the atmosphere at the escape velocity, the plasma of the double electric layer also causes interruptions of radio communications, furthermore, the electron flow occurring in the process additionally increases energy transfer to the surface leading, this way, to the explosive mechanism of burning of the heat-shielding coating.
3. When space vehicles fly at high altitudes, the emission of negative electrons from their surfaces induce positive potential of several kilovolts. That is why it is necessary to ensure continuous monitoring of the zero potential in the power supply units of on-board electronic equipment.
4. When space vehicles fly at the altitudes from 100 km to 500 km, an intense glow around the front hemispheres of the space vehicles occurs (Gretchikhin Effect) with its maximum at the altitude from 110 to 140 km. At the moment of transition from the illuminated zone to the zone of the Earth's shadow the intensity of the glow increases sharply. Practical applications remain out of sight for obvious reasons.

References

1. Johnson C. J., Keppner J. P. Daytime measurement of positive and negative ion composition to 131 km by Rocket-borne. / J. Geophys. Res. 1956, 61(3), p.575.
2. Harrie Massey. Negative ions. – London-New York-Melbourne: Cambridge University Press, 1976. -754 p.
3. Физические величины. Справочник /А. П. Бабичев, Н. А. Бабушкина, Ф. М. Братковский и др.; Под ред. И. С. Григорьева, Е. З. Мейлихова. – М.: Энергоатомиздат, 1991. – 1232 с.
4. Гречихин Л. И. Неравновесное оптическое излучение воздушных и космических летательных аппаратов. Докторская диссертация, БПИ – 1986 г. – 325 с.
5. Гречихин Л. И., Тюнина Е. С. Исследование электродных факелов дугового разряда /Физика и химия обработки материалов 1967, Т.11, №3, 27-28 с.
6. Гречихин Л. И., Минько Л. Я. Об аналогии физических процессов, протекающих в импульсном разряде и при воздействии концентрированного лазерного излучения /Журнал технической физики, 1967, Т. 37.
7. Гречихин Л. И. Взаимодействие твердого тела с окружающей средой в режиме свободномолекулярного обтекания (эффект Гречихина) /Первый Белорусский космический конгресс. //Материалы конгресса (28-30 октября 2003 г. г. Минск: ОИПИ НАНБ, 2003. -278 с. С. 31-33
8. Mc. Mahon W., Saller R., Hills R., Delorey D. Measured electron contribution to Shuttle plasma environment. «AIAA Shuttle Environ and Oper. Meet., Washington, D.C., 31 Oct. – 2 Nov., 1983. Collect. Techn. Pap.» New-York, NDG. S.a., p. 52-58.
9. Prince R.H. On Spacecraft – induced optical emission: a proposed second surface luminescent continuum component. //Geophys. Res. Lett., 1985, Vol. 12, № 7, p. 453-456.
10. Engebretson Mark J., Hedin Alan E. DE-2 mass spectrometer observations relevant to the Shuttle glow. //Geophys. Res. Lett., 1986, Vol. 13, № 2, p. 109 – 112.
11. Papadopoulos K. The Space Shuttle environment as evidence of critical ionization phenomena. «Active Exp. Space. Proc. Int. Symp., Alpbach, 24-28 May, 1983.» Paris, 1983, p. 227-244.