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THE ELECTRIFICATION OF SPACECRAFT

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16. Abstract

The booklet discusses physical and applied aspects of the electrification of space vehicles and natural celestial objects, analyzes the factors resulting in electrification of spacecraft and describes methods of investigating various phenomena associated with this electrification and ways of protecting spacecraft against the influence of static electricity.

The booklet is intended for the general reader interested in presentday questions of space technology.

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SPACECRAFT ELECTRONICS

A. I. Akishin, L. S. Novikov

Old Problems in New Technology

Once it has left the surface of Earth, a spacecraft (SC) /3*
begins a voyage through the limitless ocean of the universe,
in the vastness of which cosmic storms will deluge it with
streams of plasma, electromagnetic waves of various frequencies
and much else that constitutes the space environment. Under the
influence of these factors the SC, in particular, takes on a
certain electric charge and thus an electric potential relative
to the surrounding plasma. The sign and magnitude of the elec-
tric charge and potential depend on both the properties of the
medium in which the flight is occurring and the properties of
the SC itself, foremost the electrophysical characteristics of
the materials of its outer shell and the geometrical features
of the design.

Different parts of the SC surface may acquire different
charges: because of the different conditions of exposure of these
parts to the external factors and differences in the electro-
physical properties of the materials located at these parts.
A typical example is the acquisition of different charges by
the sunlit and shaded portions of the SC surface in a greatly
rarefied cosmic plasma. Since the surface of modern SC is 80-90%
covered with dielectric materials (heat-regulating coatings,
protective glass of the solar batteries, etc.), the potentials
of sections with different charges cannot be equalized. A

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*Numbers in the margin indicate pagination in the original text.

so-called <u>differential charge</u> is created, and electric voltages appear between individual portions of the SC surface.

In certain cases the potentials arising on the SC are negligible (tenths of a volt); in other cases they amount to kilovolts and may substantially affect the operation of the SC.

A considerable number of various instrument malfunctions /4 were registered in the first geostationary Earth satellites launched in the early 1970s (their orbit is in the equatorial plane at a height of 36,000 km). For example, certain American geostationary satellites designed for radio and television communications were prevented from normal functioning. The malfunctions occurred in the most diverse appliances of the geostationary satellites. In the electronic systems false instructions appeared for the turn on or off of equipment, the normal supply of electricity from the solar batteries was disturbed, the attitude of the antennas was spontaneously changed, etc. Usually the normal function was restored after a certain time, but there were also cases of irreversible damage. It is not appreciated when the picture suddenly vanishes during a television broadcast of an exciting hockey or soccer match. Yet the geostationary satellites transmit a large volume of the most diversified information, the loss of which in many cases would prove irreplaceable!

It was suggested that the observed anomalies are due to the differential charging of the SC to high potentials, resulting in electric discharges at the SC surface. The electromagnetic interference produced by the discharges could indeed be the direct source of the equipment malfunction.

Measurements of the parameters of the surrounding plasma afterwards conducted aboard geostationary satellites directly

indicated a charging of the satellite, in some cases to negative potentials of several kilovolts. Special instruments were subsequently installed in the satellites to record the electromagnetic interference and measure the surface potential, in order to demonstrate that the malfunctions were indeed due to the buildup of electric charges on the SC.

Static electricity has confronted mankind with many obstacles in the various realms of technological enterprise, including the serious subject of the conquest of the skies. A tiny spark produced by the discharge of static electricity was perhaps the last straw that decisively tipped the scales in favor of airplanes in their contention with dirigibles for mastery of the air in the late 1930's. In any case, efforts to use dirigibles as air passenger transportation were halted after the loss of a huge dirigible by fire caused from an electric discharge.

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This immense airship, around 250 m in length, appeared in the skies over New York on 6 May 1937, after making a three-day flight across the Atlantic Ocean from Germany to the USA. For quite some time the dirigible circled at a low height over New York and was just attempting a landing under clear signs of an impending storm. The ship was already hovering over the landing field when a flash suddenly appeared at its stern, an explosion was heard, and in moments the entire vast body of the ship, holding nearly 200,000 m^3 hydrogen, was enveloped in flame. Nearly all of the more than 100 passengers and crew perished.

The catastrophe resulted from the charging of the hull of the dirigible with atmospheric electricity in the pre-storm sky. An accidental spark ignited the mixture of hydrogen and air, resulting in the explosion and fire.

But even airplanes, which became the masters of the ocean of air, proved to be subject to the influence of static electricity

resulting from the interaction between liquid and solid particles of the clouds and precipitation. The problem grew in seriousness as the speed of the airplane increased: it was discovered that the current charging an airplane during flight in clouds and precipitation builds up with increase in velocity much more rapidly than the discharge current.

Electrical discharges of various forms and attendant electromagnetic interference and damage of structural elements were observed on airplanes. The charging of an airplane with static electricity also sharply increases the danger of lightning damage. According to the existing estimates, the likelihood of a direct hit of an airplane by lightning when flying in a storm cloud is 10^{-4}, i.e. in one out of 10,000 flights through a cloud lightning almost always strikes the airplane.

But if the airplane is electrically charged, this probability is increased by two orders of magnitude: there is now one case of lightning striking in 100 flights through the cloud. According to information of the U.S. Weather Service, half the instances /6 of lightning striking of airplanes when electric charges are present occur in clouds where generally no lightning existed prior to the appearance of the airplane. Thus, the charged airplane initiates the lightning, causing the atmospheric electricity to discharge onto itself. This is not surprising if we observe that the potential of the airplane relative to the surroundings may amount to one and a half million volts!

There have been quite a lot of reports of airplane loss from lightning. For example, this was the reason for the catastrophe of a Boeing-707 airplane on 8 December 1963 approaching a landing at the Philadelphia airport. After the lightning strike, the airplane took fire and burned up.

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Even spacecraft were destined to experience lightning discharges. Lightning twice struck the Apollo-12 spacecraft during its launch on 14 November 1969. On this occasion there was no serious damage. An inspection after the launch revealed only minor disturbances in the power system of the ship, and it was able to continue its flight to the Moon. In truth, this is nothing more than a curious incident.

But it was not long before the numerous anomalies observed in the operation of the systems of the first geostationary satellites necessitated a very serious treatment of the problem of protection of SC against "lightning" generated on board, or electric discharges caused by the differential charging of the surface.

Hence, with all the diversity in flight conditions and design of the aircraft, aerostatics, aviation and, finally, astronautics had to face a common problem - the electrification of the vehicles in flight.

Was This Unexpected?

It cannot be said that the discovered charging of satellites to high potentials was totally unexpected. The principal theoretical statements describing the process of electrification of celestial objects during their interaction with the surrounding plasma and electromagnetic waves had been formulated more than 40 years ago. In the late 1930s and early 1940s the first scientific works were published discussing the charging of particles of cosmic dust and the influence of the electric charge of the motes on their movement. The process of charging of the lunar surface was also subsequently discussed.

The beginning of the second phase in the study of the problem of electrification of cosmic bodies relates to the

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preparations for scientific experiments conducted by satellite. The research of Soviet scientists occupy a prominent place here. In 1957 the works of K. I. Gringauz, I. M. Imyanitov, B. A. Mirtov and V. G. Istomin were published, laying the foundation for the technique of measuring the parameters of cosmic plasma and electric fields in the plasma with instruments installed in a satellite. These works provided estimates of the possible influence of charging of the SC on the results of the experiments. A penetrating theoretical analysis of the phenomena occurring during the motion of a SC in cosmic plasma was made by Ya. L. Al'pert, A. V. Gurevich, and L. P. Pitayevskiy. Under the direction of I. M. Podgorniy a large program of experiments was initiated to simulate the flow of plasma around celestial objects. This yielded much valuable information, including some regarding the processes of electrification of satellites.

The third phase in the study of the problem of electrification, begun in the 1970s, relates to the investigation of the mechanisms of high-voltage differential charging of geostationary satellites and other SC and the development of techniques to deal with the problem.

Of course, this division of the history of the study of the problem of electrification of celestial objects into phases is quite arbitrary, for during each phase there were published scientific works that concerned the different aspects of the problem. We should mention that, as early as 1961, the Soviet scientists V. G. Kurt and V. I. Moroz predicted the possibility of negative charging of satellites to potentials of 15-20 kV. These values were computed on the basis of certain assumptions as to the possible relationships between the particles of low and high energy in the cosmic plasma, since the extremely sparse experimental data of the time did not yet allow a sufficiently reliable judgment as to the true values of these parameters in the various realms of outer space. /8

By the start of operations of geostationary satellites there was already a quite solid volume of theoretical and experimental data assembled on the electrification of satellites in low circumterrestrial orbits. Here the potentials of the satellites usually do not exceed several volts and are no danger to the instrument systems. But the processes occurring in high voltage differential charging of geostationary satellites proved so dangerous and peculiar that a special thorough and comprehensive investigation was required.

Despite the considerable effort directed at the study of the causes of electrification of geostationary satellites and the quest for means of coping with the problem, even today the question is rather serious. Even the new generation of geostationary satellites, designed to allow for electrification, have not yet succeeded in totally eliminating the associated anomalies, and the possibility of occurrence of such must be taken into account. It is indeed no accident that the malfunctions observed over 14 h of operation of the communications satellite TDRSS-Ey in October 1984 during the flight of the American spacecraft Challenger were initially explained by the intense flux of charged particles associated with a solar flare.

This satellite was being used to transmit information to Earth that could not be recorded on board the spacecraft. As a result of the malfunctions, the volume of transmitted information was reduced to 20-30% of the plan. Afterwards, it is true, there was a report that the cause of the malfunctions of TDRSS-Ey could also be operator errors at the ground station.

The possible effects of electrification are also designed into future space systems. Thus, the currently projected geostationary satellite solar power stations (SPS) with a power of 10 GW should have around 100 km^2 of solar batteries. The maximum

transverse dimensions of the SPS are 20-30 km, while the entire
mass is 100,000 T. It is presumed that the voltages on the
current-carrying busbars of the various equipment aboard such
SPS, in particular the equipment for transmission of electricity
to Earth in the microwave range, will amount to 20-40 kV.

The presence of such potentials on the elements of equipment
of the SPS may, on the one hand, influence the relationship
between the SPS and the surrounding plasma and, on the other,
create an additional danger of electric discharge on board the
SPS. Discharges are possible between the high-tension electrodes
and the charged sections of surface of the SPS.

Additional interest in the problem of electrification of
SC has recently involved the widespread practice of so-called
active experiments in outer space, during which beams of electrons
or ions are injected from the SC into the surrounding medium for
the purpose of studying its physical properties.[1] A whole host
of interesting phenomena are observed: artificial polar lights,
excitation of various types of wave in the cosmic plasma, etc.
But at the expense of ejecting charges of one sign the SC acquires
an electric potential of opposite sign, which retards the beam
of charged particles and thereby impedes the normal course of the
experiment. Of course, the resulting potential should be compen-
sated in some way.

The danger of charging with static electricity also exists
for the interplanetary SC, e.g. those designed to study Jupiter,
Halley's comet and others. The physical mechanisms of the
charging of these SC may differ radically from those operative
in circumterrestrial space.

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[1]Cf. Podgorniy, I. M., Aktivnyye eksperimenty v kosmose [Active
Experiments in Space], Znaniye, M., 1974.

The great diversity and importance of the questions concerning electrification of cosmic objects have created major interest in this subject. Various physical investigations in the field of SC electrification have been organized in our country on the initiative of S. N. Vernov during the last years of his life.

Further in the booklet we discuss in detail the physical /10 and practical aspects of the question of electrification of SC and natural celestial bodies, analyze the reasons for the charging of cosmic objects, and describe the methods of investigating the various phenomena concerning electrification and ways of protecting SC against static electricity.

Positive or Negative?

Just what physical processes bring about the charging of a body in outer space and determine the sign and magnitude of the electric charge or the potential of the body?

If a noncharged body is placed in an isothermic plasma, i.e. a plasma consisting of electrons and positive ions with identical kinetic energies, the body will begin to be negatively charged. This is explained by the fact that, when the kinetic energies are equal, electrons have much higher velocity than ions because of the difference in mass.

Recall that, for a given plasma temperature, the velocities of the particles are distributed around a certain most probable value (Maxwellian distribution). The mean kinetic energy of the particles is proportional to the plasma temperature and does not depend on their mass, while the mean velocity is smaller as the mass of the particle is larger. Therefore, even for the most light of positive ions - the proton (nucleus of the hydrogen

atom) - the mean velocity of thermal motion in an isothermic plasma is 43 times lower than the velocity of the electrons.

This is exactly the situation for the fluxes of particles moving from a plasma onto the surface of an uncharged body if the concentrations of electrons and protons in the plasma are equal. For this reason, electrons carrying negative charge will preferentially reach the body at the start. Afterwards the fluxes of electrons and positive ions will gradually equal out, due to the influence of the electric field produced by the negative charging of the body on the particles. This field will be decelerating to the electrons, and those with the least energy will not be able to reach the surface of the body. On the other hand, the protons are attracted by the negatively-charged surface, and their flux may increase.

A negative equilibrium potential is established when the /11 electron and ion fluxes reaching the surface of the body are equal. Naturally, in this case the absolute magnitude of the equilibrium potential is proportional to the mean energy of the electrons of the plasma, i.e. the plasma temperature, since the negative potential needed to diminish the flux of electrons increases with the mean energy of the latter. When the energy of the plasma particles is higher than several dozen eV the so-called secondary emission currents start to play an important part in the balance of currents on the surface. These currents are produced by secondary electrons knocked out of the surface when hit by the arriving electrons and ions of the plasma (primary particles).

From the sunlit portions of the surface of the body electrons are also detached by photons of the solar ultraviolet and x-rays, producing a photoelectron current which, like the secondary emission currents, carries away negative charge from the body.

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Other physical processes are also instrumental in the current balance at the surface of the body. Several of these will be discussed below.

In all cases, the equilibrium potential is determined by the fact that the cumulative current flowing across the surface of the body must equal zero. However the individual components of the current directed toward or away from the surface are not equal to zero, i.e. there is a continual transfer of charges between the surface of the body and the surrounding plasma. A change in any current component, for whatever reason, displaces the equilibrium. The cumulative current will return to zero, but at a different value of potential of the surface of the body relative to the surrounding plasma.

Usually the critical factor in the current balance at the surface of the body is the relation between the electron current of the plasma that is negatively charging the body and the photoelectron current that is compensating for the negative charge. If the photoelectron current is absent (at the non-illuminated portions of the surface) or less than the electron current of the plasma, the body is most often negatively charged. True, under certain circumstances the negative charge may be rather completely compensated by the secondary emission currents, as shall be discussed in detail below.

But if the photoelectron current exceeds the electron current of the plasma, which obtains e.g. in the interplanetary space, the body is positively charged. In the case of negative charging in outer space, as already mentioned, the potential of the body is proportional to the mean energy of electrons of the plasma and may reach minus 15-20 kV. With positive charging, as a rule, the potential of the body does not exceed 10-15 V. This value is dictated by the energies of the photoelectrons and secondary electrons leaving the surface of the body.

The Charges of Cosmic Dust and Giant Planets

The first theoretical estimates of the values of electric charges and potentials of celestial bodies were made in the early 1940s for the case of interstellar dust particles with transverse dimensions between fractions of a micrometer and several micrometers. The resulting values of the potential were between minus 1-2 V and plus 3-5 V. These estimates were quite hypothetical in nature, owing to the uncertainty of many of the parameters of the cosmic environment.

Afterwards similar calculations were made for dust particles and meteoroids in the solar system. As knowledge increased about the properties of the interplanetary environment, the calculations were frequently revised and upgraded. According to the estimates, the positive potential of dust particles in the solar system may be 10-12 V.

The charging of objects in interplanetary and circum-terrestrial space, like many other phenomena, is ultimately governed by the solar activity. A stream of plasma known as the solar wind continually emerges from the outer totally-ionized gas shell of the Sun, heated to 1 million K into the interplanetary space. The plasma of the solar wind consists mainly of electrons and protons with a low content of alpha particles (nuclei of the helium atom) and heavier positive ions. The concentrations of electrons and protons in the solar wind are identical, on the average 7 cm^{-3}.

The mean velocity of the solar wind in the proximity of Earth is around 400 km/s. Hence we may find the density of the flux of plasma particles of the solar wind: about 10^8 cm^{-2}/s.

Besides the general directed motion at this velocity, the particles of the solar wind plasma undergo a chaotic thermal

motion, the velocity of which (as mentioned above) is determined by the plasma temperature and the particle mass. Measurement data show that the plasma temperature of the solar wind is nearly 10^5 K. At such temperature the mean velocity of thermal motion of the protons is approximately 45 km/s, while that of the electrons is 2000 km/s. The protons reach the surface of objects (e.g. interplanetary dust particles) in the "wash" of the solar wind primarily by virtue of the velocity of directed motion of the plasma flux, while the electrons reach the object largely through their thermal motion.

However the dust particles in these estimates may be taken as motionless, since their proper velocity, measuring several dozen km/s, is much less than that of the plasma flux or the thermal velocity of the electrons.

The balance of currents at the surface of the dust particles must also allow for secondary electrons knocked out of the surface by the protons and electrons of the solar wind. In the solar wind the energy of the protons, occasioned by the directed velocity of the plasma flux is approximately 800 eV, while the mean kinetic energy in the thermal motion of the electrons is around 15 eV. In either case the value of the coefficient of secondary emission for the majority of materials is not above 0.2-0.25.

And finally, we should factor in the photoelectron emission from the surface under the influence of the ultraviolet and x-rays of the Sun. Measurements by rockets and satellites show that, outside the atmosphere of Earth, i.e. where the solar radiation is not weakened by absorption, the flux density of photoelectrons from the surface of various materials is between $5 \cdot 10^9$ and $3 \cdot 10^{10}$ cm^{-2}/s, which roughly corresponds to photoelectron current densities of $(1-5) \cdot 10^{-9}$ A/cm^2.

In the solar wind the nonilluminated surface of an object may acquire a negative potential of several volts, since the flux of solar wind electrons arriving at the surface exceeds the flux of protons, while the illuminated surface should be positively charged, owing to the preponderance of photoelectron current over the electron current of the solar wind plasma.

As the positive potential of the body increases, the flux of photoelectrons leaving its surface will diminish as a result of the return of some of these to the surface by the decelerating electric field, while the flux of electrons of the plasma will increase somewhat by virtue of a more effective collection. This relationship is shown in Fig. 1., The point of intersection of the curves corresponds to the equilibrium potential of the surface.
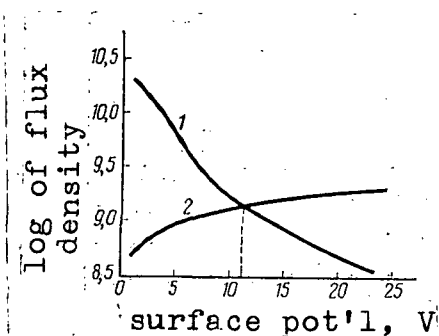

Fig. 1. Electron fluxes (in logarithmic scale) as functions of the surface potential of a dust particle: 1 - photoelectrons leaving the surface; 2 - electrons of solar wind collected by the dust particle.

The presence of a charge on cosmic dust has a dual manifestation. First, the charge influences the motion of the dust through the action of the coulomb forces from the charged particles of the surrounding plasma and the forces produced by the motion in magnetic fields. Second, the dust charge may accelerate its growth by increasing the likelihood of adherance of other dust to the charged surface. This mechanism is allotted

an important place in several hypotheses concerning the origin of the solar system.

The opposite effect is also possible - disintegration of tiny particles by the coulomb forces. Disintegration occurs if the forces of mutual repulsion acting between like-charged particles of the object exceed the critical mechanical strength of the material. It is also known that, when the electric field strength is greater than 10^9 V/m, electrons will be torn from the negatively-charged surface under the action of the coulomb forces: <u>auto-electron emission</u> occurs. This process is one of the physical mechanisms limiting the potentials of objects in outer space. /15 For an object of spherical shape, the electric field strength at the surface is equal to the ratio between the potential of the body and its radius.

In order for electrical disintegration of a particle to occur, the electric field intensity at the critical limit should not exceed the value for autoelectron emission. For example, this does not obtain in the case of stony and iron meteoroids. Consequently, these cannot be disrupted by electric forces. But for loose dust formations having a low limit of mechanical strength, the threshold strength of the electric field is much lower than 10^9 W/m, and they may be disintegrated when charged. Spherules of dust 20 µm in diameter will be shattered when the surface potential is around 100 V.

H. Fechtig and others have used this mechanism to explain the micrometeoroid (these usually include meteoroids less than 0.1 mm in size) "flashes" registered by the equipment of the satellite GEOS-2 in circumterrestrial space. It was presumed that the original noncompact particles being disrupted by electric forces were ejected from the surface of the Moon when hit by meteoroids.

The mechanisms of charging of the Moon itself are similar
to those considered for tiny dust particles. The sunlit side
of the Moon is charged by a photoelectron emission current to a
positive potential of 5-15 V. Such potentials had been theoreti-
cally predicted, and direct measurements of the energy spectra
of ions near the lunar surface confirmed them in the early 1970s.
The relation between the potential of the sunlit side of the
Moon and the angle of incidence of sunbeams has been calculated.
This is shown in Fig. 2. For normal incidence, i.e. at the sub-
solar point of the surface, the potential is a maximum, diminishing
with distance away from it.
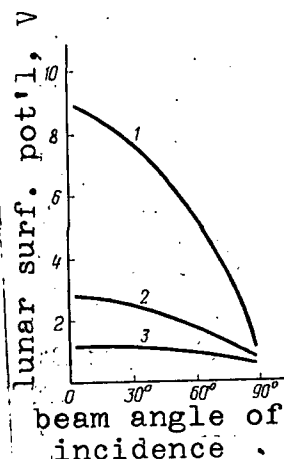

beam angle of
incidence

Fig. 2. Decrease in electric potential
of the sunlit lunar surface with
increase in the angle of incidence of
sunbeams. Curves plotted for different
values of the mean electron yield per
quantum (1 - 10^{-1}; 2 - 10^{-2}; 3 - 10^{-3}).

A negative potential is created at the nonilluminated side
of the Moon, which may be minus 50-100 V or less according to
current estimates. In some theoretical models the currents of
the particles of the extremely thin ionic gas shell of the Moon
are included in the calculation of the potential of the lunar
surface. The concentration of charged particles in this shell
is not greater than 10^2-10^{-3} cm^{-3}.

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The charging of the lunar surface has major influence on the processes of transport of lunar dust. Instruments carried by spacecraft to the lunar surface have recorded dust streams traveling over the surface at sunrise and sunset, perpendicular to the light/shadow boundary. These streams have been explained by the influence of electric forces on dust particles. The existence of dust flows above the lunar surface is also confirmed by the data of certain optical observations. Thus, the crew of Apollo-17 observed a glow at heights as far as 100 km from the lunar surface at sunrise. And photographs taken by Surveyor indicate a similar glow near the lunar surface.

Both phenomena have been explained by the scattering of sunlight on particles of lunar dust sustained above the surface by coulomb forces. The processes of electric transport of dust and electrostatic disintegration of tiny particles may perhaps also contribute to the erosion of the lunar surface.

Our planet is likewise charged. The Earth carries a negative electric charge of around $6 \cdot 10^5$ C. This charge is not very large. For example, such a charge flows through an ordinary 60 W electric bulb hooked up in a network after 25 days. Nevertheless, the presence of a distributed charge on the Earth's surface creates an electric field around it with a strength of about 130 V/m, which greatly influences the occurrence of various atmospheric phenomena.

The processes resulting in the charging of the Earth's surface are much more complex than those mentioned above. In fact, the Earth is protected against the direct action of the solar wind and the solar ultraviolet rays by the geomagnetic field and the atmosphere. The plasma flux of the solar wind, deflected by the geomagnetic field to a distance of more than 10 R_E (R_E = 6370 km is the radius of the Earth), causes a con-

traction of the field and an asymmetrical stretching of the geo-
magnetic lines of force in the antisolar direction. The solar
wind is the chief factor determining the configuration and many
of the properties of the Earth's magnetosphere, or the region
occupied by the geomagnetic field, within which charged particles
of different mass and energy travel[1].

The ultraviolet rays of the Sun are largely absorbed by the
upper layers of the Earth's atmosphere, resulting in the process
of ionization of the atmospheric gases. This is instrumental in
the formation of the ionized region of the upper atmosphere of
Earth - the ionosphere. The ionosphere takes up the height inter-
val between 60 and 1000 km. Its upper bound is usually specified
by convention, since the ionosphere gradually changes into the
next plasma shell of the Earth, or the plasmosphere, which extends
to heights of around 4-6 R_E.

The negative charge of the Earth is produced and sustained
nearly constant by the interaction of the Earth's surface with
the atmospheric layers near the ground. It is believed that the
drain of negative charge from the Earth's surface to the atmosphere
occurs largely as a result of conductance of the near-ground layer
of air, while lightning plays a large part in the return of charge
to the surface. Each second there are about 100 lightning flashes
above the Earth, and each bolt carries a charge of 10-50 C.

Numerous observations have convincingly demonstrated that
changes in the parameters of the solar wind and the short wave
solar electromagnetic radiation affect the occurrence of many
processes in the lower atmosphere and at the surface of Earth,

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[1]For more details cf., e.g., Dubinin, E. M., Podgorniy, I. M.,
Magnitnyye polya nebesnykh tel. [The Magnetic Fields of Celestial
Bodies], Znaniye, M., 1980.

including the transfer of charge between the Earth's surface and
the atmosphere. This interaction is mediated by a number of
processes taking place in the atmosphere and ionosphere. In
recent years important progress has been made in the under-
standing of magnetosphere/ionosphere correlations and correla-
tions between the upper and lower atmospheric layers. But many
details of the overall picture still remain unclear.

Still largely enigmatic are the electric properties of
the cosmic environment in the proximity of giant planets remote
from us. Voyager-1 and Voyager-2 have registered a thin dust.
ring around Jupiter, the formation of which may be attributed
to the action of electric forces on charged dust particles.
Incidentally, Voyager-1 was itself charged to potentials between
-40 and +50 V at distances of 10-25 radii from Jupiter. This
was when the SC was illuminated by the Sun. But in the absence
of sunlight the SC may have been charged to -10 kV in this region,
as indicated by calculations on the basis of available data as
to the magnetosphere of Jupiter. In fact, certain of the mal-
functions of Pioneer-10 and Pioneer-11 near Jupiter have been
explained by the charging to high potentials.

An interesting hypothesis explains the modulation of the
decameter radio waves of Jupiter by the existence of a powerful
current system between the magnetosphere of the planet and its
satellite Io. According to the hypothesis, the current carriers
are photoelectrons emitted by the sunlit surface of Io and parti-
cles of the magnetospheric plasma. An electric voltage of around
10^6 V is induced on Io by moving in the magnetic field of Jupiter.

Voyager-1 also furnished intriguing information as to the
structure of the rings of Saturn. Wavy formations were dis-
covered, classified as "braids" and "spokes". It is believed
that these also result from the action of electromagnetic forces

on dust particles of micrometric size that are charged in the nonilluminated portion of the magnetosphere of Saturn.

Thus, electric charges play an extremely important part in the "fate" of both insignificant cosmic dust and enormous planets. As we have seen, their influence is also large on the functioning of artificial celestial objects and various types of SC, as shall be further discussed.

Flight in the Ionosphere

The first estimates of the possible charging of a satellite in the late 1950s, on the threshold of the space age, naturally involved the conditions of flight in the ionosphere. First, the launching of the first satellites was planned for relatively low circumterrestrial orbits and, secondly, virtually nothing was known at the time as to the properties of the cosmic plasma at greater distances from Earth. In fact, the radiation belts of Earth were not even discovered yet, the structure of the magneto-sphere was unknown, and even the word "magnetosphere" did not exist in its current understanding.

However information had already been obtained as to the charged particles in the ionosphere from radar probing and some few launches of research rockets, carrying instruments to heights of several hundred kilometers. But even these data were highly approximate, particularly for heights greater than 250-300 km, which are not accessible to radar investigation from the Earth's surface. In fact, at these heights the concentration of free electrons and ions in the ionosphere reaches a maximum on the order of 10^6 cm^{-3}, slowly diminishing with greater height.

Therefore, radio waves reflected from the region of maximum electron concentration (the major ionospheric maximum) and from

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lower-lying regions may return to Earth. But if the length of
the radio waves sent from the Earth becomes less than a certain
critical value they will escape into outer space without reflec-
tion from the ionosphere. The measurement of the parameters of
the Earth's ionosphere at great height was in fact one of the
chief missions to be solved by satellite.

The temperature of the ionospheric plasma is nearly 1000 K,
while the corresponding kinetic energy of its particles is
0.1 eV. It may be computed that the velocity of the electrons
will be around 200 km/s, while that of the positive ions only
1 km/s. The latter figure pertains to ions of atomic oxygen,
which are the prevalent ionic constituent in the ionosphere at
heights greater than 300 km. But a satellite travels at a speed   <u>/20</u>
of 8 km/s in the ionospheric plasma. We again confront a situa-
tion similar in part to the case of charging in the solar wind:
the magnitude of the electron flux is determined by their thermal
velocities, whereas the ion flux reaching the object is governed
by the velocity of the directed transport. But unlike this
situation, the ions can now be taken as motionless, while the
moving satellite is prodded against them with its forward sur-
face.

In the ionosphere the density of the isotropic flux of
electrons onto the surface of an uncharged satellite and the
density of the directed flux of positive ions are much larger
than the maximum density of the flux of photoelectrons from the
sunlit surface of the satellite. Consequently, the photoelectron
current cannot be important in the charging of a satellite in the
ionosphere. However in some cases - e.g. analysis of the opera-
ting conditions of certain instruments installed aboard the
satellite, and the plasma characteristics near its surface - the
photoelectron current must be taken into account.

Because of the low energy of the particles of the ionospheric plasma, secondary emission currents from the surface are also nearly absent in this case. Because of the motion of the satellite, the energy of impact of ions with the surface increases to several eV, but even such energy is not enough for the ions to produce a notable secondary emission from the surface. True, the ions may additionally knock out secondary electrons by the so-called potential mechanism of secondary emission. This is based on the neutralization of an ion near the surface of a body, accompanied by transfer to the electrons of the energy spent in formation of the ion, i.e. ionization of the neutral atom. But for the majority of ionospheric components in realistic conditions the secondary emission produced by this mechanism is too small.

Thus, in the ionosphere the surface potential of a satellite is determined by the relation between the electron and ion currents in the surrounding plasma. From the preceding discussion it is clear that the satellite should acquire a slight negative potential, roughly corresponding to the thermal energy of the electrons.

We should, however, factor in another important effect /21 influencing the charging of a satellite in the ionosphere. As follows from the velocity relationship, the ions chiefly arrive at the front surface of the moving satellite, while behind there is formed a region with lowered concentration of ions - the ion shadow. The concentration of electrons behind a moving satellite is much less affected, because of their high thermal velocities. Therefore electrons preferentially reach the satellite surface facing the ion shadow, encouraging an increase in the negative potential at this surface and a differential charging of the satellite.

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The effect of formation of the ion shadow is compensated by the influence on the motion of particles in the proximity of the satellite by the electric field created by the charged surfaces and the magnetic field of Earth. Even so, the potential of the rear surface of the satellite may be increased by several fold beyond the value found without the ion shadow. It must be admitted that the analysis of the flow of plasma around a satellite is extremely difficult and, as a rule, requires complicated calculation techniques.

Potential differences between the individual portions of a satellite may also be induced by its movement in the geomagnetic field. Estimates show that the motion of a conductor 1 m long perpendicular to the geomagnetic lines of force at the heights of the ionosphere at a velocity of 8 km/s produces a voltage on the order of 0.4 V between its ends. The thus-induced electric voltages usually have to be considered as perturbations in various kinds of measurement. For example, in the measurement of electric fields in the ionosphere and magnetosphere.

The negative potentials of a satellite surface actually observed in the ionosphere are as high as 3-5 V. Such potentials usually are no threat to the instrument systems of satellites but, as already mentioned, may disturb the functioning of various kinds of probes, ion traps and other instruments designed to study the ionospheric plasma. In the case of differential charging, even very low potentials may produce electric discharges at the surface of the satellite and between individual elements of its structure. (Remember the electric sparks produced by closing <u>/22</u> the contacts of the battery of a pocket flashlight!)

The electromagnetic interference created in this way is perceived as outside noise by the scientific instruments. In connection with the recent use of highly sensitive probes aboard

satellites, operating by the registration of various plasma
resonances in the radio band, such interference must be controlled.

The charging of a satellite also affects its orbital para-
meters. Calculations show that the action of coulomb forces
from the surrounding plasma on a charged satellite cause a fur-
ther deceleration in addition to that produced by impact between
the satellite and the neutral particles of the upper atmosphere.
Also instrumental in the deceleration are effects involing induc-
tion (in the metal parts of the satellite) of eddy currents
through motion in the geomagnetic field. These effects are
factored into the calculation of the satellite orbits at iono-
spheric height and in the determination of the density of the
upper atmosphere from the satellite deceleration.

In discussing the charging of a satellite at low circum-
terrestrial orbits (200-1000 km high) we have assumed that it
is only surrounded by relatively cold ionospheric plasma. How-
ever when flying above the polar regions of the Earth the satellite
may be subjected to the intense fluxes of electrons with energies
between 0.1 and 50 keV that penetrate the upper atmosphere from
the magnetosphere and produce the polar lights.

Through the Curtain of the Polar Lights

The enchanting spectacle of the sky observed in the polar
regions has long attracted the attention of mankind. Mention of
this grand display may be found in the works of many ancient
chroniclers and philosophers. There have also been many attempts
to explain the nature of the polar lights. Their connection
with electrical processes in the upper atmosphere of Earth was
suggested as far back as M. V. Lomonosov, who wrote: "It is
highly likely that the northern lights are generated by electrical
force originating in the air."

In the late XIX century it was already clear that the aurorae are caused by the emission of light by excited atoms and molecules of gases in the upper atmosphere. By the early 1950s the optical spectra of the polar lights had been studied quite thoroughly by ground observations. But only quite recently, after massive information was obtained through satellites and rockets as to the structure of the magnetosphere and the characteristics of the streams of particles penetrating the upper atmosphere, was it possible to construct an adequate and sound physical model of the formation of the polar lights.

This model is based on the concept of the penetration of particles of the solar wind into the depths of the magnetosphere and their acceleration in the magnetosphere and subsequent showering into the upper atmosphere. The polar lights are observed most often above two oval regions situated asymmetrically about the magnetic poles of the Earth. On the night side the oval of the polar lights, or the auroral oval (in honor of the goddess of the dawn, Aurora), is situated at approximately the 70th geomagnetic parallel; on the day side, the 80th. During intense geomagnetic disturbances the auroral oval is displaced far to the south, so that the aurorae may be observed e.g. in Moscow or lower latitudes.

The asymmetrical shape of the auroral oval and its displacement are caused by the structure of the magnetosphere, from which electrons with energies on the order of 0.1-50 keV in a flux density of as much as 10^{10}-10^{11} cm^{-2}/s penetrate the upper atmosphere of Earth along the geomagnetic lines of force. The atmospheric luminescence produced by the excitation of its atoms and molecules by the electrons is observed at heights from 100 to 800-1000 km. The exceedingly variable forms of the polar lights reflect the spatial and temporal distribution of the fluxes of invading electrons. The width of the bright arcs and rays of the aurorae usually does not exceed several km.

The polar lights are also caused by the penetration of protons with energies around 1-100 keV into the upper atmosphere, although the flux density of the proton showers is around three orders lower than that of the auroral electrons.

Hence, if the orbit of a satellite flying at 200-1000 km passes through the zone of the polar lights, it may be exposed to fluxes of auroral electrons in addition to the ionospheric plasma. The flux density of the auroral electrons may exceed $\underline{/24}$ the density of the oncoming flux of positive ions. As a result, the satellite will be charged by the auroral electrons. Since their energy (0.1-50 keV), determining the size of the negative potential of the satellite, is much higher than the energy of electrons of the ionospheric plasma (0.1 eV), the latter very quickly cease to reach the satellite or take part in its charging.

However the question arises: doesn't the high negative potential of the satellite produce an intense gathering of the positive ionospheric ions by its surface, so that the satellite will discharge?

Calculations and experimental studies show that the electric field in the ionosphere produced by a negatively charged satellite will penetrate the surrounding plasma only to a distance of around 1 cm from the surface, so that the satellite is shielded by a layer of positive ions. Therefore as the negative potential of the satellite increases the flux of positive ions at its surface grows very slowly. This growth is less as the ratio is larger between the size of the satellite and the distance of shielding of the electric field, or so-called Debye length. As a result, equilibrium is achieved only when the surface potential is sufficiently negative.

Fig. 3 shows the results of calculation of the equilibrium potential for a nonilluminated satellite exposed to a flux of

auroral electrons with mean energy 7.5 keV in an ionospheric plasma with charged particle concentration 10^5 cm^{-3}. It is evident that, as the flux density of auroral electrons increases, the negative potential of the satellite first grows very quickly, but then this growth slows down. The slope of potential buildup and its equilibrium value are larger for a satellite with larger radius R_0.

The findings were obtained without considering the perturbations of the ionic plasma by the moving satellite or the influence of the geomagnetic field on the paths of the charged particles. More rigorous evaluations should also include these factors, which may notably affect the process of the charging.
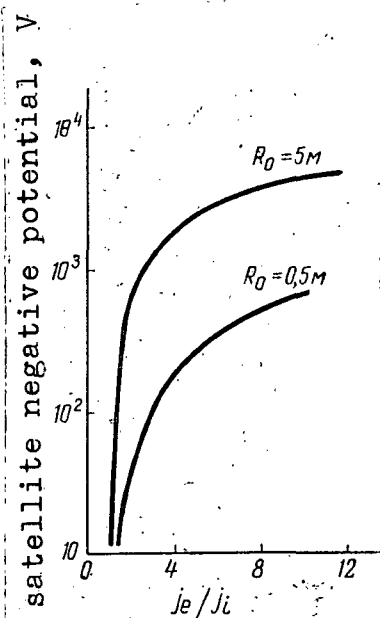
Fig. 3. Growth in negative potential of a satellite with increase in the ratio between the flux density of auroral electrons j_e and the density of the oncoming ion flux j_i (R_0 is the radius of the spherical satellite).

Since the time of crossing the arc or ray of the polar
lights by the satellite may be small (around 0.1 s for an arc
1 km wide), the evaluation of the equilibrium potential should
also take into account the time rate of its buildup. The rate
of .charging of the satellite is governed by the magnitude of the
charging current and the capacitance of the satellite relative
to the surrounding plasma, while in the case of differential
charging it is also governed by the local capacitances formed
by the various structural elements on the surface of the satellite.
We shall return to this question. Here we merely point out that
the intensity of the flux of auroral electrons is sufficient to
charge a satellite to high potential in a time of 0.01-0.1 s.

Effects similar to those discussed may also occur in the
inverse situation, when charged particles with energies of
dozens or hundreds of keV do not arrive at the surface of a
satellite, but are ejected from the satellite into the surrounding
plasma by means of some kind of apparatus.

Will an Accelerator Work in Outer Space?

Experiments with injection of beams of charged particles
from satellites or rockets into the surrounding cosmic plasma,
as already mentioned, have been widely conducted in the past
decade. Without doubt, such organization of scientific experi-
ments represents a considerable advance in space research.

Indeed, from the passive registration of various processes
in outer space it has become possible to advance to a directed
and controllable initiation of such with investigation of the
resulting phenomena by spaceborne and ground instruments. Thus,
the space experiments have become similar in their organization
to laboratory experiments, while remaining free of the con-
straints imposed by laboratory installations (disparity between

the space and time scales, influence of processes at the walls
of vacuum chambers, inaccurate replication of the characteristics
of the space environment, etc.).

The various physical phenomena of interaction between an
injected particle beam and a plasma occur and are observed more
clearly when the plasma is sufficiently dense. Therefore
experiments with injection are often performed at ionospheric
heights, using meteorological rockets to lift the charged
particle accelerators. The interaction between the beam and
the ionospheric plasma may occur in either the region of injec-
tion or in the opposite hemisphere when the injected particles
are transported along the geomagnetic lines of force.

The first experiments with injection of electrons into the
magnetospheric plasma from rockets were conducted in 1969/70.
However the theoretical elaboration of such experiments was
begun approximately 10 years earlier. Obviously, when an elec-
tron beam is emitted in an ideal vacuum the rocket will begin
to acquire a positive charge, but when its potential becomes
equal to the accelerating potential of the electron gun (creating
the electron beam) the escape of electrons into the surrounding
space will stop, since they will be returned by the positive
potential to the surface of the rocket.

When such an experiment is conducted in the ionosphere the
positive charge of the rocket may be neutralized by electrons
of the surrounding plasma reaching its surface.

But if the injected current exceeds the compensating
electron current gathered by the SC surface from the surrounding
plasma, the danger of positive charging of the SC and halting
of the injection of electrons remains, i.e. the danger of dis-
turbance of the normal course of the experiment. The charging

of the SC may occur very quickly. For example, a sphere of 3 m diameter with an injection current of 0.5 A and an injected electron energy of 10 keV is charged to a positive potential of 10 kV, corresponding to the stoppage of the injection, in no more than 10^{-6} s.

Taking into account the possibility predicted by such analysis of the stoppage of operation of an electron accelerator aboard a spacecraft, the first experiments with injection endeavored to create a large conducting surface for the gathering of ionospheric electrons. With this aim, various kinds of deploying collectors, "umbrellas", thin-film inflatable structures with conducting coating and others were designed. Thus, in the very first experiment with electron injection, carried out in January 1969 under the direction of W. Hess, pulsed electron beams up to 1 s in duration with maximum current of 0.5 A and electron energy of 10 keV were injected into the ionosphere from a rocket ascending to a height of 270 km. Ionospheric electrons were gathered by a collector of aluminum foil, roughly 530 m^2 in area, which was deployed after the rocket had passed through the dense layers of the atmosphere.

However it was rather soon found that, even without such gathering collectors, the positive potential of a SC when injecting electron beams with energy of dozens of keV into the ionosphere seldom exceeds 100-200 V. This was demonstrated e.g. by the experiment Zarnitsa-1, conducted in our country in May 1973, and by subsequent experiments of Soviet scientists.

In the experiment Zarnitsa-1, from a rocket at heights of 100-160 km an electron beam was injected into the ionosphere with approximately the same parameters as in the experiment of Hess; however the compensating electron current was collected solely by the rocket hull. The electron accelerator operated

normally, while during its functioning near the rocket there was observed a glow interpreted as the ignition of a gas discharge in the area around the rocket. Thus, the necessary compensating current may be provided not only by increasing the electron-gathering surface, but also by altering the parameters of the plasma in the proximity of the rocket.

This process may vary according to the situation in the ionosphere. At heights of around 100 km, where the concentration of neutral particles in the atmosphere is still quite high (around 10^{13} cm^{-3}), while the length of the mean free path of injected electrons prior to collision with neutral particles is comparable to the dimensions of the SC, the concentration of charged particles near the rocket will be notably increased by ionization of the neutral atmosphere through the injected electrons.

Ionization of the neutral atmosphere is also achieved by electrons gathered on the surface of the rocket. The extra electrons formed by these two processes may significantly increase the current compensating for the positive charge of the rocket.

To achieve a steady state in the ionization of neutral particles of the atmosphere at heights of around 100 km requires roughly the same time as the charging of the SC with the injection current. Therefore the positive potential of the SC should be efficiently compensated from the very start. But as the altitude increases, the time for achieving a steady state of ionization increases, reaching around 10^{-3} s at a height of 200 km. Consequently, in the height range of 100-200 km there may be transitional processes characterized by a rapid buildup in positive potential of the SC immediately after initiation of the beam, and a more gradual decrease in proportion to the ionization of neutral particles in the area around the rocket.

Above a height of 200 km, where the concentration of neutral particles becomes less than 10^{10} cm^{-3}, while the concentration of charged particles of ionospheric plasma is 10^5-10^6 cm^{-3}, the injected electrons travel to many kilometers from the SC with virtually no collision of either neutral or charged particles. In this case, the interaction between the injected electron beam and the ionospheric plasma is electromagnetic in nature. The beam injection excites electromagnetic oscillations in the surrounding plasma, whereby the energy of the injected electrons is transferred to the plasma particles.

In such a situation an electric discharge may be ignited between the electron beam and the surrounding plasma (beam-plasma discharge). A discharge develops when the plasma electrons taking on the additional energy become capable of ionizing the neutral particles of atmosphere. In turn, the secondary electrons that result will be accelerated by the electromagnetic fields excited in the plasma, and will ionize the neutral particles. As a result, an avalanche will ensue, producing an intense compensating current onto the SC surface, from which the electron beam is injected.

There is also another physical model for the ignition of a discharge near a SC at great heights, according to which the plasma electrons take on an energy sufficient to ionize the neutral particles as a result of their acceleration toward the SC, cutting across the geomagnetic lines of force. The electrons will rotate about the SC, causing an ionization of neutral atoms and molecules.

As we observe, in order for electric discharges to develop there should be a sufficient quantity of neutral gas particles in the vicinity of the SC. In certain cases, even at considerable height, such concentration may be sustained at a level of

$10^{10}-10^{12}$ cm^{-3} by the natural gas exhaust of the SC. Thus, there are adequately effective physical mechanisms to prevent a strong buildup in SC potential when injecting electron beams into the ionosphere at heights between 100 and 400-500 km, as confirmed by experiments.

We should however note that the injection of beams of positive ions, which are useful e.g. in studying the structure of the geomagnetic field and measuring the electric fields in the magnetosphere, may result in high negative potentials on the SC. This is similar to the case of charging of a SC by auroral electrons in the ionosphere.

The compensating ion current gathered from the surrounding plasma in this case is less than the electron current gathered during the positive charging. Furthermore, no ignition of discharge in the vicinity of the SC is observed with the injection of ion beams.

We point out yet another item of importance in regard to technique. The accelerator emitting electrons is joined to the metal hull of the SC, which is also positively charged when the accelerator is working. But the outer surface of the hull, as mentioned, may be coated with nonconducting heat-regulating paint, enamel and so on. As a result, the electrons collected from the plasma accumulate at the dielectric surface, forming a /30 kind of capacitor, one plate of which is the metal hull of the SC, the other the charged surface of the dielectric. If the dielectric is thin, and the energy of injected electrons is sufficiently large, the strength of the electric field in the dielectric may surpass its electrical strength and electrical breakthroughs will begin between the surface of the dielectric and the hull of the SC.

Such danger exists e.g. on a reuseable transport space-craft (RTSC), more than 95% of the surface of which (1300 m^2) is covered with nonconducting material. According to present estimates, during the injection of a 10 A electron beam at a height of around 400 km the potential difference between the nonconducting surface and the metal hull of the RTSC may reach dozens of kV in the space of 0.1 s.

Until now we have been discussing the charging of a SC surface by charged particles from the surrounding space. But as shall be shown below, charging may also occur from the action of neutral atoms and molecules, as well as dust particles.

A Brief Encounter with a Celestial Wanderer

In the first half of March 1986, cosmic envoys of Earth - two Vega spacecraft (USSR in cooperation with several European countries), Giotto (the European Space Agency) and Planet-A and MS-T5 (Japan) - will encounter Halley's comet when the latter will be traveling at a speed of around 50 km/s between the orbits of the Earth and Venus.

This comet has already played a major role in the history of astronomy, being used to prove that comets belong to the solar system. After discovering the comet in late August 1682, the 26-year-old English astronomer E. Halley, together with I. Newton, who had recently formulated the law of universal gravitation, calculated the orbits of a number of comets and proved that they may travel about the Sun along greatly elongated ellipses. Previously it was believed that comets enter and leave the solar system in random fashion, traveling straight through interstellar space. Using the results of the calculations and information from <u>/31</u> historical chronicles, Halley determined the periodicity of appearance of his comet (around 76 years) and predicted the time of its next appearance.

And now Halley's comet will have a new "debut" - it will be the first comet to unfold its secrets to instruments encountering it in orbit. Unfortunately, this encounter will be transitory in the literal sense. Halley's comet travels about the Sun in a direction opposite the motion of the planets. Therefore SC launched from Earth will fly toward the comet at a speed nearing the orbital velocity of the Earth (30 km/s). As a result, the speed of movement of the SC relative to the comet at the encounter will be around 80 km/s, or somewhat smaller, depending on the orbital parameters of the SC.

With such large relative velocity the instruments will fly through the gas and dust shell of the core of the comet in no more than several minutes, and past the core itself (3-4 km in diameter) in tenths of a second. And during this brief time the SC instruments are to conduct a number of measurements involving the study of the comet's core and investigation of the chemical composition of the gas and dust particles in the comet's atmosphere, the degree of ionization of the comet's atmosphere, etc.

The flight of a SC through the atmosphere of a comet is somewhat similar to the motion of a satellite in the Earth's ionosphere, but the concentration of surrounding particles and the parameters characterizing the interaction between the oncoming flow and the SC surface will be very different (Table 1).

For a relative velocity of 69 km/s, with which the SC Giotto should pass through the comet's atmosphere, there will be a kinetic energy of 24 eV for each atomic unit of mass of the oncoming particles. The kinetic energy of the typical comet gas molecules H_2O and CO_2 will be respectively 432 and 1056 eV. Having such kinetic energy, the neutral molecules will be able to knock out electrons, positive and negative ions, as well as

Table 1. Anticipated parameters of the atmosphere of Halley's comet

Basic Parameters	Distance from the Core, km	
	10 000	500
Concentration of neutral particles, cm^{-3}	10^5	10^9
Concentration of charged particles, cm^{-3}	10	10^4
Density of oncoming flow of neutral particles, cm^{-2}/s	10^{12}	10^{16}
Average speed of thermal motion of ions and neutral particles, km/s	3	
Average speed of thermal motion of electrons, km/s	600	
Average kinetic energy of electrons, eV	1	

neutral particles from the SC surface. The latter process will be the most effective.

In the case of a gold-covered surface, a single gas particle of the oncoming flux may knock out 1-2 neutral atoms, i.e. the material of the surface will be pulverized. The pulverization effect should be considered in the choice of thickness of the various protective coatings, but may only indirectly affect the charging of the SC - through a change in the surface state. However the processes of knockout of charged particles from the surface directly result in charging of the SC. The effectiveness of knockout of secondary electrons and secondary ions under such conditions is much lower. /32

Table 2 presents the densities of the fluxes of charged particles across the surface of a SC flying at a distance of around 10,000 km from the core. The secondary electrons and ions are knocked out by the oncoming flux of neutral particles. The flux of electrons of the surrounding plasma at the SC surface is determined by their thermal velocity, while the ion flux is

determined by the approach velocity. The flux density of photo-
electrons is assumed to be the same as that near the Earth.
Secondary emission of electrons under the action of the oncoming
ion flux is not considered, as this flux is small. The last
column of the table shows the sign of the charge produced on the
SC surface by each particle flux, although the indicated flux
density values refer to the initial time, when the surface of
the SC is not yet charged.

Table 2. Flux density of primary and secondary charged particles
across the surface of a SC flying in the atmosphere of Halley's
comet at a distance of 10,000 km from the core

Type of Particle	Flux Density, cm^{-2}/s	Sign of Charge Produced on the Surface
Secondary electrons knocked out by neutral particles of the oncoming gas stream	$(0,2-0,4)\cdot 10^{12}$	+
Secondary ions (positive)	10^6	—
Electrons of surrounding plasma (isotropic flux)	$1,5\cdot 10^8$	—
Ions of surrounding plasma (oncoming flow)	$7\cdot 10^7$	+
Photoelectrons	$3\cdot 10^{10}$	+

It is clear from Table 2 that the predominating component
at the front surface of the SC is the current of secondary
electrons knocked out by neutral particles. A state of equili-
brium here should set in at positive potential, owing to the
limited current of the secondary electrons and the gathering of
electrons from the surrounding plasma. The mean kinetic energy
of the secondary electrons is 10-20 eV. The positive potential
of the forward surface of the SC will also correspond to this
energy.

As the SC encounters the comet the Sun will illumine its

forward surface and one of the sides. At the sunlit side in absence of an oncoming gas flow the photoelectron emission current will predominate, charging the surface to a positive potential of 3-5 V. But as the SC approaches the core of the comet the electron current of the plasma will grow, and at a distance around 1000 km from the core it will exceed the photoelectron current, so that the SC surface will take on a negative potential.

The shaded side of the SC is instantly charged by the electron current of the surrounding plasma to a negative potential of several volts, similar to the situation in the ionosphere of Earth. In analogous fashion the rear of the SC is charged, but its negative potential may be higher on account of the formation of the ion shadow behind the SC.

Thus, a SC with nonconducting surface may be differentially charged upon flying in a comet's atmosphere. The maximum potential difference is created between the front and rear surfaces of the SC. The magnitude of this potential difference at a distance of 10,000 km from the core of the comet, according to the above estimates, should not exceed 30-40 V. But if the SC has a conducting surface the potential will be +10-20 V. /34

An even more rigorous modeling of the process of differential charging has been done by computer for the SC Giotto, enabling a study of the structure of the electric field around the SC. The findings revealed that, at close approach to the comet core, the potential difference between the front surface of the SC and its hull may possibly reach 200-500 V.

The presence of the spacecraft's own electric fields in the vicinity may distort the instrument readings used to investigate the comet's plasma. Moreover, the characteristics of the plasma itself are changed near the SC as a result of the penetration of

a large number of secondary charged particles knocked out of the SC surface. The largest changes, as follows from Table 2, are those of the plasma in front of the SC, caused by the flux of secondary electrons knocked out by neutral particles.

Such phenomena have already been experimentally observed during the flight of the Pioneer/Venera spacecraft in the atmosphere of Venus. With a SC velocity of 10 km/s, the CO_2 molecules present in the atmosphere (concentration 10^9 cm^{-3}) knocked out electrons from the front surface of the SC in such numbers that the resulting electron concentration was equal to $2 \cdot 10^4$ cm^{-3} at a distance of 40 cm from the surface. A definite determination of secondary electrons with an energy of 2-3 eV was made against the background of the natural ionospheric electrons with energy of around 0.1 eV.

Extrapolation of this finding to the flight conditions of Giotto in the atmosphere of Halley's comet, along with mathematical estimates, indicated that the concentration of secondary electrons in front of the SC flying at 10,000 km from the core will be 10^3 cm^{-3}, which is 100 times larger than the electron concentration in the surrounding plasma. Without doubt, this effect must be considered in the measurement process and the interpretation of the findings.

There have also been laboratory studies of the charging of a SC surface exposed to a high-velocity gas flow. Bombarding a target with neutral argon atoms with an energy of 1 keV produced a charging of the target to positive potentials of 10-20 V, in agreement with the given estimates.

We have mentioned that, besides the atoms and molecules of various gases, dust particles are contained in the comet's atmosphere, which likewise form an oncoming flux at the SC sur-

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face. True, it is not yet clear what kind of dust this is. In fact, the study of this dust is one of the major missions of the SC being dispatched to the comet. However, dust particles enter the comet's atmosphere by evaporation of the core. Therefore they should consist of ice with more or less content of mineral impurities. The dimensions of the dust may obviously vary from fractions of a micrometer to hundreds of micrometers or more. But the shape of the particles should necessarily approach the spherical. In particular, experiments involving the polarization of sunlight scattered by comets indicate the presence of a large number of oblong dust particles in the atmospheres of comets.

The concentration of dust particles at close distances to the comet core (500-1000 km) is perhaps only slightly lower than the concentration of neutral gas particles. During a high speed collision between the dust and the SC surface both the dust particle itself and the material of the SC shell should be melted and evaporated. Because of the high temperature in the impact zone (tens of thousands of K), a considerable portion of the evaporating atoms and molecules are ionized, i.e. a plasmoid is formed near the surface upon impact, which will then expand into the surrounding space.

Incidentally, the phenomenon of formation of plasma during high-speed impact will be used to study the elemental composition of the comet dust. The essential information is to be obtained by analysis of the ion composition of the plasma.

According to estimates for the SC Giotto, the flux of secondary charged particles formed by impact of dust particles against the SC surface may at a distance of 500 km from the comet core exceed the flux of electrons knocked out by neutral gas particles by nearly an order of magnitude. Since electrons

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and positive ions are formed in equal amounts by thermal ioniza-
tion of vapor, the bombardment of the SC surface by the dust
particles apparently should not result in a charging.

At the same time, laboratory experiments have frequently
observed a somewhat larger yield of electrons as opposed to
positive ions during microparticle collisions. It has not yet
been definitively established whether this is the result of
registration of a particular electron background created in the
vacuum chamber (e.g. the functioning of an accelerator of dust
particles or electron emission from the walls of the chamber)
or whether the increase in the electron component is due to the
action of other physical mechanisms of electron emission. If
the latter is true, the oncoming dust flow may create a positive
charging of the SC.

Disturbance of electrical equilibrium is also possible from
the different ways in which the resulting electrons and ions with
substantially different masses and initial velocities leave the
SC surface.

The unique nature of the upcoming experiments investigating
Halley's comet necessitates an especially careful analysis of
all phenomenon associated with the influence of the surrounding
environment on a spacecraft, including the SC charging processes
and modification of the surrounding plasma as discussed herein.
With this we shall conclude our imaginary voyage to the comet and
again return to the magnetosphere of Earth to discuss matters
relating to the charging of geostationary satellites to high
potentials.

What is the Source of Hot Plasma?

But just why are geostationary satellites subject to charging

to high negative potentials?

Recall that the magnitude of the negative potential of the satellite is proportional to the temperature of the electron component of the surrounding plasma. Thus, when charged to a high potential the satellite should dwell in a hot plasma, for which it is necessary that the electron current of the plasma negatively charging the satellite to exceed in magnitude the currents that might remove the negative charge from the satellite. /37

It turns out that such conditions may occur in the magneto-sphere of Earth in the altitude region of 30,000-50,000 km, exactly where the geostationary orbit occurs (height roughly 36,000 km). During geomagnetic disturbances from increased solar activity a plasma with particle energy of 5-30 keV may reach these altitudes from the tail of the magnetosphere, i.e. the night side.

We may imagine the following very simplified picture of the process of injection of hot plasma into the region of the geo-stationary orbit during geomagnetic disturbances (magnetospheric substorms). During heightened solar activity and solar flares there is an increase in the speed of the particles of the solar wind and, consequently, a greater compression of the magneto-sphere by the flux of plasma of solar wind moving about its periphery. The constriction of the geomagnetic field in the tail of the magnetosphere, which is the site of the so-called plasma layer that contains a plasma with particle energy of 1-5 keV, is in fact the cause of the injection of this plasma deep within the magnetosphere. Sometimes the injection process is illu-strated more vividly by the model of a "toothpaste tube": the constriction of the geomagnetic field "forces" plasma from the region of the magnetosphere tail, similar to toothpaste from a tube.

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The plasma particles are further accelerated in moving into the magnetosphere, so that their mean energy at the altitudes of the geostationary orbit is 5-30 keV. Reaching the zone of rather strong magnetic field of the Earth near the geostationary orbit, the particles of penetrating plasma may be separated by this field: the electrons carrying negative charge drift preferentially to the east, or the dawn sector of the magnetosphere, while the protons carrying positive charge move to the west.

At the same time as the hot plasma arrives at the night side of the geostationary orbit, the density of cold plasma diminishes. The energy of its particles is close to 1 eV. The plasmosphere is somewhat constricted during geomagnetic disturbances: cold plasma is forced from higher altitudes closer to the Earth's surface. The constriction of the plasmosphere is /38 asymmetrical in longitude: the greatest displacement of cold plasma from the high altitudes occurs in the region of the midnight meridian and in the dawn sector: from 00:00 to 06:00 local time.

As a result of these processes a geostationary satellite during magnetic substorms in the night and early morning hours may be exposed to a flux of hot plasma exceeding the flux of cold plasma; in some cases the temperatures of the electron and proton components of the hot plasma, as well as the concentrations of electrons and protons of the plasma, may be different. It is this that causes the negative charging of the satellite to potentials roughly corresponding to the temperature of the hot plasma.

Although this scheme of the geophysical processes resulting in the charging of geostationary satellites is highly incomplete, it rather adequately explains the experimentally-observed

mechanisms of equipment malfunctions of geostationary satellites.
Fig. 4 shows the time distribution of malfunctions according to
the data of a number of American geostationary satellites. It
is clear that malfunctions occur primarily in the early morning
hours. Fig. 5 illustrates the correlation between the occurrence
of malfunctions and the appearance of hot plasma in the region of
the geostationary orbit. There is also data testifying to a
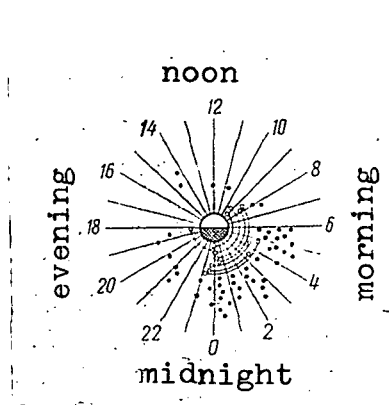higher rate of malfunction with increasing level of geomagnetic
activity.

Fig. 4. Time distribution
of instances of anomalous
instrument operation ob-
served aboard geostationary
satellites. White circles
joined by arcs indicate
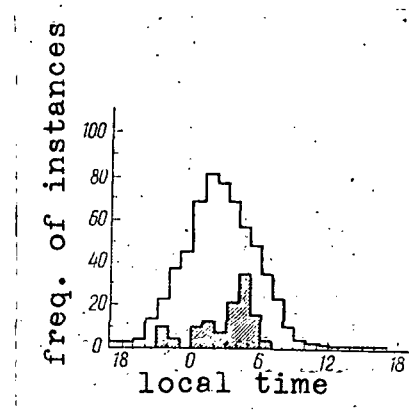cases where the time of
onset of the malfunction
is not exactly known.

Fig. 5. Comparison of the
frequency of instrument
malfunctions of the geo-
stationary satellite
Marex-1 (upper limit of the
hatched zone) with the fre-
quency of appearance of
electrons with energy above
1 keV at a flux density
greater than 10^9 $(cm^2 \cdot s)^{-1}$
in the region of the geo-
stationary orbit (upper
curve).

Measurement results show that the maximum flux density of
electrons of hot plasma at a noncharged geostationary satellite
may approach 10^{10} cm^{-2}/s. This, as a rule, is still below the
flux density of photoelectrons from the surface of the satellite.

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Therefore a slight positive potential appears at the sunlit
side of the satellite, whereas the nonillumined side is nega-
tively charged. This, as already mentioned, results in the
differential charging of the satellite surface.

It should be mentioned that even at the night side of the
orbit one side of a geostationary satellite is usually sunlit.
Only during the spring (approximately 21 March) and autumn
(23 September) equinoxes may a geostationary satellite at great
height above the equator be in the Earth's shadow, and then only
for around 1 hour. The reason for this is the tilting of the
Earth's axis toward the plane of the ecliptic.

Fig. 6 shows the difference in potential reliefs on a
sunlit geostationary satellite when its surface is either con-
ducting or nonconducting. At the left is the situation for a
satellite with conducting surface, at the right nonconducting.
The arrows depict the fluxes of charged particles. For simpli-
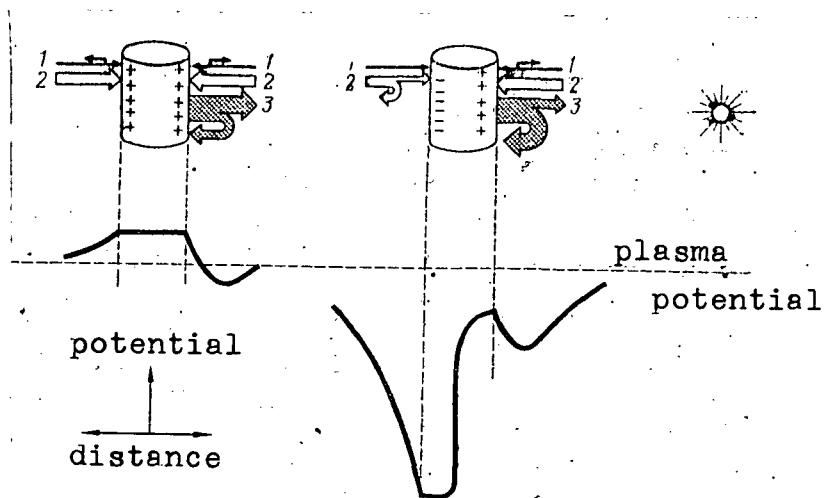city, the secondary emission currents are not shown.

Fig. 6. Difference in the conditions of charging
of a SC with conducting or nonconducting surface
in sunlight at one side: 1 - flux of positive
ions (protons) of plasma; 2 - flux of electrons
of plasma; 3 - flux of photoelectrons.

If the satellite surface is conducting, excess electrons from the nonillumined side can move freely to the sunlit side, whence they are removed by the photoelectron emission current. As a result, the satellite surface is positively charged. At the nonillumined side the potential in the space around the satellite monotonically decreases and gradually approaches the plasma potential. At the sunlit side there may be a local minimum in the potential distribution, resulting from the electron space charge; it is even possible for the potential to become negative in the region of the minimum.

In the case of a nonconducting surface the nonillumined side of the satellite is negatively charged by the electrons of the plasma. If the size of the negative potential at the nonillumined side is considerable, the potential of the sunlit side may also reach the negative region, as shown on the right of Fig. 6, although it remains higher than the potential of the nonillumined side. A sizeable potential gradient will arise in the region of the terminator (light/shadow boundary) on the surface of the satellite. The potential distribution in the space around the satellite at the sunlit side may in the present case show the same features as a satellite with conducting surface.

However the occurrence of a potential minimum here may result not only from the space charge, but also the inherent characteristics of the electrical field structure near the satellite. The process of differential charging, as already mentioned, is also conditioned by the design and electrophysical properties of the materials and the surface of the satellite.

Thus, a qualitative analysis of the charging of geosta- tionary satellites may be performed on the basis of rather elementary and vivid physical ideas. But the calculation of the potentials on the various portions of the surface, especially

for a satellite of complicated configuration, at times requires an extremely elaborate mathematical apparatus and is usually done by computer. In the following section we provide several examples of such calculations.

A Satellite in Mathematical Grids

The computation of the potential of any given surface element of a satellite in a cosmic plasma basically comes down to the solving of the current balance equation for this element. It is necessary to write the algebraic sum of all the currents flowing through the chosen element of surface of the SC or satellite, equate this to zero (which is what the establishment of equilibrium signifies), and solve the resulting equation in terms of the potential.

However this seemingly simple calculation scheme is extremely difficult to implement in practice. Difficulties occur right from the writing of the expressions for the currents flowing from the plasma to the surface of the satellite in the process of its charging. These currents depend on the surface potential of the satellite, since the electrons of the plasma are repelled from the surface by the resulting negative potential, while protons are attracted to the surface.

Relatively simple expressions describing the relation between the plasma currents and the surface potential of a satellite can only be written for objects with geometrically elementary surface: spherical, cylindrical or planar. In these cases the plasma currents can be described by equations found as far back as the 1920s by the American physicist I. Langmuir for the process of collection of electric charges on the surface of a tiny electrode placed in the plasma of a gas discharge. Such an apparatus, often known as a Langmuir probe, is still used to investigate plasma parameters.

If no electrical voltage is applied to the probe from an outside circuit, it will be charged to a certain potential determined by the temperature of the plasma. This equilibrium potential is known as the free probe potential, or the floating potential. Thus, the process of charging of a satellite is to some extent analogous to the establishment of the floating potential on the probe. But unlike the case considered by Langmuir, the secondary emission currents flowing across the surface play an important part in the charging of a geostationary satellite by hot cosmic plasma. The analytical description of these currents also involves no little difficulty.

For example, the secondary electron emission determined by the coefficient δ first increases with the energy of the primary electrons (E), reaching a certain maximum δ_{max} at an energy of around 500 eV, and then gradually diminishes as the energy further increases. This relation between δ and E is associated with the variation in depth of penetration of primary electrons into the material and the probability of emission of secondary electrons with increasing energy E.

A similar relationship is observed in the case of the knock-out of secondary electrons by protons, but the maximum emission of secondary electrons is achieved at much greater proton energies. With just these relationships for nonmonoenergetic fluxes of primary particles, the mathematical expressions are extremely complicated.

Moreover, the coefficient of secondary emission further depends on the type of material, condition of the satellite surface, angle of incidence of primary particles and even the actual process of charging of the satellite, which produces an electric field in the thin layer of dielectric near the surface. Even an approximate analysis of the influence of these factors

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is exceedingly complicated. That is why the sufficiently rigorous analysis of the charging of the surface of even geometrically simple objects in a cosmic plasma requires the use of a computer.

A convenient method of analysis that clearly exemplifies the role of the individual components of the total current in the charging of a satellite is the plotting of the volt/ampere curves, relating the primary and secondary currents to the surface potential. As an example, Fig. 7 shows such curves plotted for a gold-covered spherical surface of a satellite as applies to the case of plasma at the geostationary orbit. Here the $/43$ curves j_e and j_p show respectively the absolute values of the electron and proton currents of plasma across the surface of a spherical satellite.
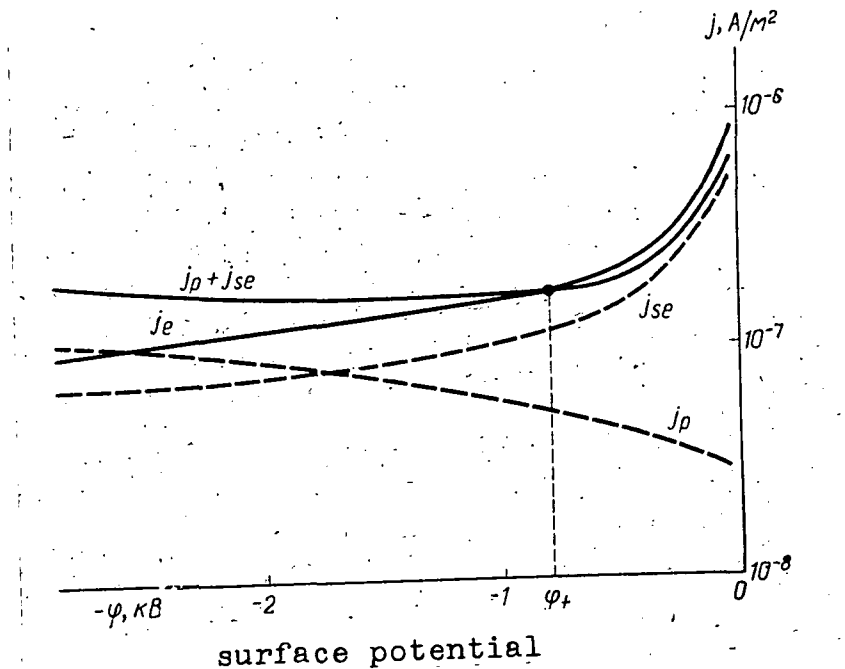

surface potential

Fig. 7. Primary and second currents as functions of the surface potential of a satellite.

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The electron current diminishes with growth of the negative surface potential, whereas the proton current increases. The secondary electron emission current j_{se} diminishes in accordance with the decrease in the primary electron current j_e. The point of intersection of the curves j_e and $j_p + j_{se}$ determines the equilibrium potential of the surface ϕ_f, which in the present case is -0.8 kV. It is also clear from Fig. 7 that, in the absence of secondary electron emission, the equilibrium potential would be -2.7 kV, which corresponds to the point of intersection of curves j_e and j_p.

Such analysis of the charging of objects in cosmic plasma has led to a whole host of important results. For example, it has been found that the resultant current across the surface of materials with large secondary emission factors may vanish at three different surface potentials, one of which (the middle one) is unstable, while the other two are stable. A so-called threshold effect has also been found: when the plasma temperature is below a certain threshold value an object placed in the plasma will not be negatively charged. The threshold plasma temperature beyond which negative potentials are produced is not the same for different materials.

Both these effects are related to the compensation of the primary electron current of the plasma by the secondary electron current. The conditions of the compensation depend greatly on the initial energy of the primary electrons, the surface potential and the secondary emission characteristics of the surface. In practice, these effects may result in different kinds of potential gradients on the satellite surface under comparatively slight changes in the parameters of the surrounding plasma or the secondary emission characteristics of the satellite surface. The onset of equilibrium in such case would depend on the initial surface potential.

If we know the size of the currents that charge and discharge the satellite surface we may estimate the characteristic times of the charging. These differ greatly for the case of general charging (i.e. charging of the satellite as a whole) and the case of differential charging. In the former case the time of the charging is determined by the capacitance of the satellite relative to the surrounding plasma, usually not greater than 1000-2000 pF, and is roughly equal to 0.3 s. In the second case, that of differential charging, there is a buildup and redistribution of the charges at the capacitances formed by the charged surface of the dielectric coatings and the hull of the satellite.

When the coatings are thin, these capacitances are sizeable. Therefore the time necessary for the differential charging of the satellite may amount to several minutes or even tens of minutes. If the parameters of the surrounding plasma change rather quickly, a steady state of differential charging may not even be attained.

Table 3 provides an idea as to the potentials to which various materials may be charged on the surface of a geostationary satellite. We point out that these potentials have been computed for conditions of moderate geomagnetic activity, when the flux density of plasma and its temperature correspond to a certain medium level. During high geomagnetic activity the /45 values of the equilibrium negative potentials may be 2-3 times greater.

The equilibrium potentials ϕ_f are computed for a plane and a sphere. It is evident that the size of the equilibrium potential depends greatly on the shape of the satellite surface. When $\delta_{max} \sim 2\text{-}2.5$, the aforementioned effect of uncertainty of the equilibrium potential may occur. The last column gives the value of the threshold plasma temperature in energy units.

Table 3. Parameters characterizing the charging of materials in the plasma of the geostationary orbit under moderate geomagnetic activity

Material	δ_{max}	plane φ_f, V	sphere φ_f, V	T_0, eV
Gold	1,45	—41	—40	2930
Aluminum	0,97	—5390	—1410	0,0
Aluminum oxide	2,6	+1,9 / —420* / —4900	+4,6 / —630* / —750	1270
Quartz	2,5	+1,5 / —640* / —4120	+3,9	1710
Aquadag	0,75	—5890	—1560	0,0
Beryllium bronze	2,2	+1,9 / —560* / —3430	+4,7	1350
Fluoroplastic	3,0	+2,3 / —490* / —4870	+5,2	1430
Polyamide	2,1	+1,4 / —170* / —6040	+3,9 / —170* / —1580	470

*Indicates unstable potentials.

It is even more difficult to compute the potentials at different parts of an object of intricate shape, such as a realistic satellite. The electric field around a satellite is created by all the charged structural elements: the hull, the solar battery panels, the various instrument components mounted on the hull, etc. Therefore the three-dimensional structure of the field in close proximity to a satellite, represented by the lines of force and the lines of equipotential, is extremely complicated. The field pattern is complicated even further by differential charging of the satellite. /46

In summary, it is virtually impossible to obtain analytical expressions for objects of developed geometry to describe with

sufficient validity the behavior of the primary and secondary currents in the process of charging of the objects. In this case the currents are computed by repeated solving of the equation of motion for the individual particles in the electric field about the object, i.e. by calculation of the paths of the individual particles.

The distribution of potential about an object is found by solving the appropriate equations in three-dimensional space. The space about the body will be broken up in some way into individual elements by the process of constructing three-dimensional grids. Such a division of the space allows the calculation to be reduced to the solving of a system of comparatively simple equations written for each element of the grid. The number of equations in the system corresponds to the number of spatial elements and may reach 10,000. This figure is arrived at by a compromise between the requirements of sufficient detail in the analysis of the structure of the electric field and the constraints stemming from the technical capabilities of the computer.

Since the characteristic dimensions of a satellite amount to several meters, the analysis of the structure of an electric field near a satellite should make use of a grid with a dimension no larger than 10 cm. At the same time, adequate precision in the calculation of the paths of the plasma particles during the analysis of the charging of a geostationary satellite requires a knowledge of the field structure up to distances of 0.5-1 km from the satellite. If the grid interval is kept unchanged, the volume of computations would be exceedingly large. Therefore during the calculation the satellite is usually surrounded by a series of such special mathematical grids with the dimension of the intervals increasing in proportion to the distance from the satellite, as shown in Fig. 8.
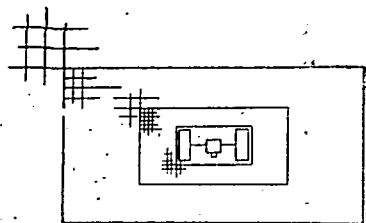
Fig. 8. Construction of a three-
dimensional grid with increasing
interval.

Such mathematical techniques enable an analysis of differ-
ential satellite charging, an exploration of the evolution of
the process of charging over time, an investigation of the
structural features of the electric field about the satellite
and on its surface, and a prediction of possible sites of
occurrence of electrical discharges. Such preliminary computer
modeling of the effects of electrification is currently becoming
a standard practice of satellite design.

At the same time, much attention is devoted to the experi-
mental investigation of satellite electrification, both directly
in outer space and in laboratory conditions, as shall be dis-
cussed hereafter.

The Potential of a Satellite Can Be Measured

The fact that the electric potential of a satellite
influences the instrument readings of the measured parameters of
the outer space plasma (Langmuir probes, charged particle traps,
electrostatic analyzers of various types, etc.) can be used to
determine the sign and magnitude of the resulting potential.
The essential information is contained in the resulting experi-
mental data. For example, with negative satellite charging the
energy spectrum of electrons of the surrounding plasma as regi-
stered by the spaceborne instruments is displaced toward lower

energies, while the energy spectrum of protons is displaced
toward higher energies.

Observation of the proton spectrum is more convenient for
such measurements. The displacement of the energy spectra is
equal to $e\phi$, where ϕ is the potential of the satellite, while
e is the charge of the electron. In just such way the negative
potentials have been measured for the geostationary satellites
ATC-5 and ATC-6, launched respectively in 1969 and 1974, yielding
a large volume of information as to the electrification of
satellites in geostationary orbit. The probability of charging   /48
of a satellite to -10 kV in the interval from 00:00 to 06:00
local time was around 10%. But at isolated times the negative
potential of ATC-6 amounted to 20 kV.

The numerous instrument failures observed in geostationary
satellites necessitated ever increasing use of spaceborne
instruments to study the effects of satellite electrification.
Thus, there were 150 serious malfunctions during the four years
of operation of the West European weather satellite Meteosat-1,
launched in geostationary orbit in November 1977. These failures
did not result in the loss of the satellite, but were the cause
of a major loss of information transmitted to Earth.

It was assumed that the malfunctions were caused by charging
of the satellite. However there was no direct proof of such
theory. The next satellite of the series, Meteosat-2 was
launched in June 1981. On board were two special instruments
which furnished data to eliminate all doubt as to the causes of
the numerous failures aboard Meteosat-1.

The spectrometer of this satellite was able to register
charged particles in the energy interval of 50 eV - 20 keV.
Another instrument, by means of a sensor mounted on the outside

of the satellite, recorded the electrical signals occurring at the instant of electrical breakthrough at the surface. By means of these instruments it was convincingly demonstrated that charging of the satellite occurs when electrons with energy of around 20 keV penetrate to the geostationary orbit, and electrical discharges occur on the satellite surface that result in malfunctions.

Various kinds of special induction sensor have been developed and used to measure the local electric fields at the satellite surface. In this way it is possible to study the processes of differential satellite charging.

To measure the electric potentials in space at various distances from the satellite, sensors are placed on outlying rods or flexible tethers. A group of such devices, stationed at various points of the satellite and oriented in a definite manner, enables an investigation of the potential distribution in the proximity of the satellite and the structure of the surrounding plasma envelope. The capabilities of such measurement /49 systems may be expanded by moving the sensors in space.

There have been interesting efforts to employ electron beams to measure the electric and magnetic fields in the space around a satellite, e.g. those undertaken with the satellites of the series GEOS. During such measurements, electrons are emitted from the satellite and again return to its surface by traveling along the closed trajectory under the influence of the electric and magnetic fields on the moving charged particles. However this measurement technique is not yet adequately developed.

The special satellite SKATKhA was launched for a more complete study of electrification of geostationary satellites in a near-geostationary orbit (apogee 43,240 km, perigee 27,550 km,

inclination 7.9°) in January 1979 in the USA. This satellite
was designed to study the radiation conditions in orbit, the
effects of satellite charging and electrification of various
materials situated on the outside surface. Fig. 9 shows a
general view of the satellite (weight 227 kg, diameter 1.3 m,
length 1.5 m). The satellite has several outlying rods to hold
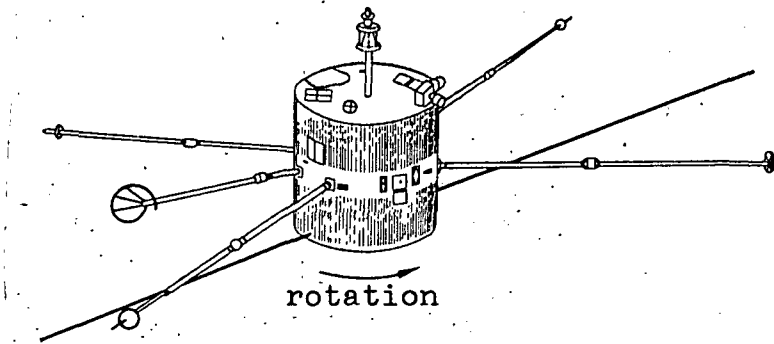instrument pickups.

rotation

Fig. 9. General view of the
satellite SKATKhA.

Practical research with this satellite answered the fol-
lowing basic questions: determination of the electric poten-
tials on the surface of various common materials of space
technology; measurement and analysis of electromagnetic noise
created during electric discharges on the surface of materials;
investigation of degradation of materials of the outer surface
of the satellite and assessment of the level of fouling of the
surface with the products of the vehicle's own atmosphere.   /50

The presence of an electron gun with maximum accelerating
potential of 3 kV and current of 6 mA aboard SKATKhA permitted
a charging of the satellite relative to the surrounding plasma,
similar to that in active experiments. While the electron gun
was working there were electrical discharges and even two equip-

ment malfunctions, coinciding in time with the most intense discharges. This was a direct proof of the possibility of equipment malfunction resulting from electric discharges on the surface of a satellite.

The first year of operation of the satellite SKATKhA revealed a high level of electrification. For example, on the morning of 24 April 1979 the surface was charged to -340 V, even in sunlight. But when the satellite was briefly in the Earth's shadow on the same day a surface potential of -8 kV had been registered. It is believed that, if the same conditions had prevailed around the satellite in the shadow portion of the orbit as during the sunlit portion, the satellite could have been charged to a potential of -15 kV.

The data acquired aboard SKATKhA enable a comparison of the charging parameters observed under full-scale conditions with the results of mathematical modeling of the electrification processes and the results of satellite or mockup testing in simulation vacuum chambers. Such testing shall be mentioned below.

Satellite Electrification in the Laboratory

The processes of satellite charging and discharge phenomena at the surface of dielectric materials may be effectively investigated with satellite mockups and the actual objects in large simulation chambers.

In particular, a 2/3 mockup of the satellite SKATKhA was /51 tested in a chamber. The testing was done with nonmoving mockup and with a mockup rotating in the course of the experiment. The mockup was exposed to electron beams with energy of 8 keV at a current density of around 10^{-9} A/cm^2, produced by four electron guns. To simulate sunlight, a source of ultraviolet rays was

installed in the chamber. Near the surface of the mockup a pickup of the electric field strength was moved to investigate the potential distribution over the surface of the satellite.

A good agreement was found between the mathematical and the experimental data. When the mockup was exposed to electrons, electric discharges were also observed on its surface. The discharges occurred when the negative surface potential exceeded 2.5 kV. The frequency of discharges increased with buildup in electron energy and current density of the beam. The duration of the discharge pulses was less than 10^{-6} s.

For realistic spacecraft such testing could furnish much useful information, although it is very expensive and, moreover, the serious danger exists that undetectable damage will occur in the complex electronic systems during the testing, only to appear when the satellite is operating in orbit.

In practice, more available and simple procedures are used. Thus, the noise immunity of the instruments is tested aboard an actual satellite by exposing it to electric arc discharges, the basic parameters of which simulate the electric discharges occurring at the surface of the dielectric coatings of the satellite in the realistic conditions of space.

The electric arc discharge produces a dual effect: an electromagnetic field that produces interference in the onboard cable network and currents that travel across the contacts and connections between the satellite's units and subunits. In simulating the effects of discharges on a satellite one analyzes the reaction of its most critical subunits and, if necessary, introduces the appropriate alterations to correct or moderate the adverse influence of electrification.

Another aspect of simulation testing of satellite mockups in vacuum chambers involves the checking of the mathematical models for SC electrification. Such experiments let us evaluate how correctly the mathematical models predict the nature of the electric fields and the distribution of charges both on the SC surface and in the surrounding space.

Besides investigating the charging of SC mockups with very accurate replication of design features, numerous experiments are conducted on material specimens in simulation chambers to study the various physical phenomena occurring under exposure of the dielectrics to beams of charged and neutral particles, electro-magnetic waves and artificially-created micrometeor particles.

Several such experiments have been already mentioned. One of the important trends in such research is the study of pro-cesses of irreversible damage of dielectrics when charged by electron and ion beams.

Electronic Disintegration of Dielectrics

When dielectric materials are irradiated by electrons with energy of 20-30 keV a certain portion of the electron flux is captured by the surface layers of materials at a depth of around 10 μm, creating an excess charge and a large electric field strength within the dielectric. As a result, the various char-acteristics of the materials are altered (electrical conductance, electrical strength, optical and mechanical properties). If the electric field strength in the dielectric exceeds 10^8 V/m, there may be electrical breakthroughs from the region of the internal charge to the surface of the dielectric or to surrounding metal structural elements. A breakdown in a dielectric produces a branching treelike discharge channel: the so-called Lichtenberg figure.

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As a result of the discharge channels, the optical and mechanical characteristics of dielectrics sharply deteriorate and there may even be failure of SC elements made from them.

This process is aggravated when the dielectrics are exposed to charged particles with energies of around 1-10 MeV, as are characteristic of the Earth's radiation belts (ERB). The electrons of the ERB penetrate to a depth of several millimeters in dielectrics, creating a danger of more extensive material failures than those of surface charging. A similar process may occur when a satellite is exposed to high-energy protons. In the event of formation of artificial radiation belts of Earth or when flying across the magnetosphere of Jupiter, the electrification of the SC dielectric materials will be intensified, as the flux density of electrons and their mean energy in such formations may greatly exceed the fluxes and energies of the particles in the natural ERB.

/53

The amplitude and distribution of the charge across the depth of the dielectric depend on both the energy and flux of particles, and on the properties of the material: the type of charge traps in the forbidden zone of the dielectric and its natural and radiation conductivity. The temperature of the SC material is also important.

The coefficient of capture of slowed electrons in dielectrics (e.g. optical glass) at room temperature is several percent. But when the dielectric is refrigerated to cryogenic temperatures nearly all the incident electrons are captured. Accordingly, the integrated electron flux per unit of surface of the dielectric for the occurrence of a breakdown is also decreased by many tenfold.

Fig. 11 shows the nature of increase in the electric field

strength in the volume of a dielectric with increase in the integrated electron flux.

Over the course of time the internal electric charge is relaxed. The relaxation time of the internal charge in different materials varies in broad limits: from fractions of a second to several years. This process depends both on the type of energy traps in the forbidden zone of the dielectric and the other electrophysical properties of the materials.
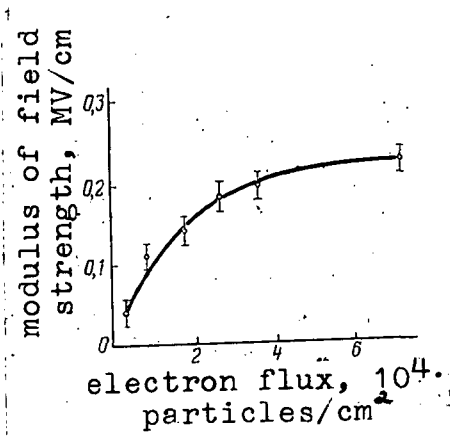

Fig. 11. Modulus of the electric field strength at a distance of 1.5 mm from the irradiated face of a specimen of alkaline borosilicate glass as a function of the electron flux.

The internal electric fields participate in the slowdown of a particle beam entering the dielectric and alter the depth distribution of absorbed energy. The energy losses of the particles in a charged dielectric are governed not only by the moderating ability of the substance, but also by the deceleration of the internal electric field. This effect is the basis for the measurement of internal electric fields in dielectrics by exposing them to "fast" electrons from radioactive sources.

/54

In transparent dielectrics the electric fields may be determined by passing polarized light through the material and observing

the effects associated with the optical anisotropy of the material. Methods have also been developed for probing the internal charge by shock waves created in various ways.

In addition to spontaneous breakdown that occurs when the electric field strength in a dielectric reaches a critical value of around 10^8 V/m, breakdowns in charged materials may also be triggered by some kind of external action. In this case they occur when the original electric field strength in the material is below the critical.

For example, breakdown in a charged dielectric may be initiated by a laser pulse. If a laser beam is focused in the volume of a charged dielectric, a local optical breakdown in the latter will occur in the electromagnetic field of the light wave, which acts as a kind of "trigger mechanism" for the break-down of the internal charge. Breakdown may also be initiated by the impacts of micrometeoroids against the surface of a charged dielectric. Such phenomena have often been observed in laboratory experiments. Near the point of impact there is a sharp increase in the conductance of the material by the forma-tion of a shock wave and concentration of the electric field, resulting in breakdown. /55

It should be expected that, under the conditions of outer space during a satellite flight in the zone of the ERB, the optical systems, fiber and integrated optics, cryogenic techno-logy and the dielectrics of the microelectronics may be extremely sensitive to radiation electrification effects.

Occasionally the radiation electrification of dielectrics in space may also have a useful application, in particular in the radiation protection of the SC by utilization of electro-static repulsion of electron fluxes by a charged dielectric shield.

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But on the whole the phenomenon of electrification is certainly a hindrance to the functioning of the systems of a SC, causing (as we have seen) both reversible and irreversible damage. Evidently, SC electrification cannot be entirely prevented, but by using various techniques can be notably moderated and the most harmful types of effect limited. We shall discuss this in the following section.

How to Deal with Electrification?

The methods of reducing SC electrification and protecting the onboard systems against the effects of static electricity can be divided into passive and active. Passive methods are currently the principal ones used aboard geostationary satellites and other SC. They include special methods of designing the SC so that the units and subunits have good electric contact with the metal hull of the SC. Special attention is paid to the reliability of the electrical connection of the shielding jackets of the numerous electrical cables to the hull, etc. The SC design should have the minimum possible number of apertures, cracks, sharp projections, to lower the likelihood of formation of greatly different electric fields.

Fiber optic communication systems within a SC have an excellent prospect for enhancing the resistance of the electronic modules of a SC to electromagnetic noise.

Current conducting materials or coatings should be used in all possible cases to prevent differential charging of the SC. /56 For example, a heat regulating coating for satellites has now been developed on the basis of waterglass with a filler: a pigment of zinc orthotitanate having high electrical conduction. In this coating virtually no electrostatic charge is built up during simulation testing. The coating has excellent optical

parameters and high radiation strength.

Transparent conducting films are used to remove the electric charge from various polymers (polyamide, fluoroplastic, etc.) commonly used in modern SC. The technology of applying conductive transparent films with additives of indium oxide (90%) and tin oxide (10%) to the surface of the dielectrics is based on the technique of plasma sputtering in a controlled oxygen-argon atmosphere. These films produce almost no change in the thermooptical properties of the original material.

The conductivity of polymers is also increased by modifying their structure and applying thin conductive networks of metals and metal oxides. The modification of the polymers is done by introducing conducting complexes into their composition. The possible methods of applying conductive networks to the surface are based on the technology of photolithography and application of thin electrodes. Films of polyamide with applied conductive network are much less retentive of electric charge on their surface than similar films with no network, exposed to the identical electron beam with energy as high as 25 keV at a current density of $3 \cdot 10^{-8}$ A/cm^2 (Fig. 12).
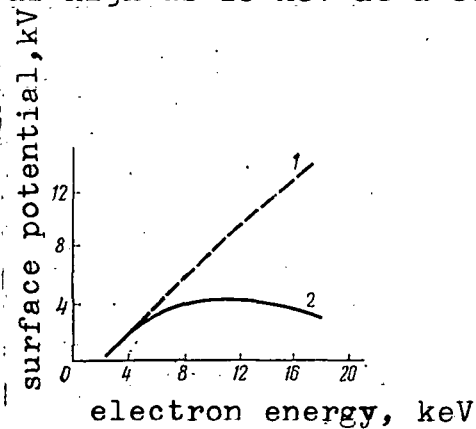
Fig. 12. Equilibrium potential of irradiated material as a function of the electron beam energy: 1 - polyamide (kapton); 2 - polyamide with metal screen applied to its surface.

The thermooptical characteristics of such polyamide are little affected, since the deposited metal screen occupies only around 6% of its surface. It has also been established that polyamide gradually increases the electrical conductance under the action of the ultraviolet rays of the Sun. This effect may evidently be used to diminish the differential charging of SC.

One of the interesting methods of lowering the equilibrium potential at the surface of a dielectric (in particular, fluoroplastic metallized at the reverse side) exposed to electrons is based on creating numerous tiny open-ended pores in it. The diameter of the pores is around 100 µm, while the amount is several dozen pores per cm^2. Such a material processing technology can lower the equilibrium potential by several fold. The mechanism of the decrease in the surface potential of the dielectric is attributable to the leakage currents from the surface through the pores to the metal layer.

The use of current-conducting materials and coatings in SC design has been successfully implemented e.g. in the development of the geostationary satellites GEOS. The operation of these satellites has demonstrated that the level of differential charging has been significantly lowered.

Insufficient attention to the question of electrification during the SC design phase may result in numerous malfunctions during operation. Such was the case with the already-mentioned West European satellite MAREX-1, launched on 20 December 1981 to operate in an international maritime communications satellite system, especially the relay of distress signals sent out by emergency radio beacons. Owing to the high level of electrification on this satellite there were frequent malfunctions. The launching of the next satellite of this series was specially delayed to introduce modifications in the design for the purpose of reducing the level of electrification.

At present, the active methods of regulating the electric potential of SC are much less developed. These methods are based on the use of various electron and ion guns to remove the excess charge from the SC. Basically, the same technique is used as in /58 the active space experiments previously described. But while in the active experiments the emission of a beam of electrons or ions from an originally-uncharged SC resulted in an adverse charging, in the present case the emitted beam of particles is able to remove the excess charge of the SC.

Such technical devices have been successfully tested aboard the satellites ATS-5, ATS-6, SKATKhA and others. However the use of active methods of removing excess charge from SC encounters a number of difficulties. The charge can only be effectively removed from the conducting surfaces and elements of the SC; the differential charging is not adequately removed, and in some cases may even be aggravated; the injectors require additional electrical energy for their power, and special equipment to control their operation and monitor them. In this connection the possibility of using passive electron emitters is also being studied. These are based on the creation of an autoelectron emission from numerous needles.

The influence of the dense fluxes of cold plasma present in the vicinity of a SC on the processes of its electrification (in particular the jet of the plasma engines) is also being studied. It has been found that the creation of such plasma formations in the proximity of a SC may effectively lower the level of electrification. Such phenomena have been studied e.g. by German and Japanese scientists in simulation vacuum chambers. A mathematical modeling of a similar situation has also been done to evaluate the energy losses of solar batteries.

Further careful study of the methods of compensating for

SC charge by means of various emitters of charged particles and plasma sources, and the development of the necessary hardware, will surely expand the future use of active methods of controlling the phenomenon of SC electrification.

Conclusion

In concluding the discussion of the most important physical /59 and practical aspects of the problem of SC electrification we should touch on several unsolved problems, as well as the prospects for future research in this field.

Despite the relative simplicity and elegance of the original physical formulation of the problem, the analysis of the electrification of realistic SC has proved exceedingly difficult, owing to the complicated geometry of the SC, their use of many dielectric materials with differing electrophysical characteristics, the uncontrollable alteration of these characteristics during the course of operation of the SC, the influence of disturbances due to the motion of the SC on the trajectories of charged particles in the proximity of the SC, and so on.

From the early 1970s to the present the study of the question of electrification of space objects has basically been organized as an independent scientific discipline making use of specially developed theoretical and experimental research methods. The American physicist G. Garrett, actively involved in this field, has described the situation thus: "On the whole, many tens of millions of dollars and thousands of man-years of work have had to be spent on understanding the details of the problem whose general theoretical description was given by Langmuir as far back as 1924."

Nevertheless, a number of important aspects of the question

of electrification require further careful study. We have mentioned that the process of charging of materials depends greatly on their secondary emission properties and conductivity. These characteristics of materials undergo considerable changes under the influence of the factors of outer space. But the nature of the resulting changes is still very little studied.

The theoretical description of satellite electrification at ionospheric altitudes, particularly in the auroral zone, is not yet adequate; the influence of the geomagnetic field and disturbances of the plasma by the moving satellite must be included in the analysis. There are also difficulties in the description of the processes occurring during the operation of charged particle injectors and plasma sources on board a SC.

The questions of focusing and defocusing of electrons and /60 ions by electric fi[ields][1]... require a detailed study, and specific recommendations should be developed for the disposition of scientific measuring instruments aboard a SC and the subsequent interpretation of their readings. Further efforts are certainly needed to investigate the intrinsic nature of the electric discharges on the surface and in the volume of dielectrics, as well as develop methods of lessening the adverse effects of electrification of materials.

It may be anticipated that, as space engineering and technology are developed, and new operational orbits achieved, and new types of SC created, the significance of the question of SC electrification will continue to grow. The gigantic satellite solar power stations of the future will have to operate for dozens of years without repair in geostationary orbits, i.e. in

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[1]In the original a line of type may have been omitted [Tr].

the zone of heightened electrical danger. Many interplanetary SC will also have to be reliably protected against effects of electrification.

The adoption of designs with high electrical voltage, techniques of electrostatic protection of SC against radiation, fiber and integrated optics, and cryoelectronics in the construction of spaceborne instruments will require a further delving into the question of SC electrification and improved methods of protection against the effects of static electricity.

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