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STUDY OF SOLAR PLASMA NEAR MARS AND ALONG THE EARTH TO MARS PATH BY MEANS OF CHARGED PARTICLE TRAPS ABOARD THE SOVIET SPACECRAFTS, LAUNCHED IN 1971-1973

I. Techniques and devices

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Moscow, 1974

SUMMARY

Experiments on the study of plasma near the Mars and along the Earth to Mars path which were performed aboard the six spacecrafts launched in 1971 and 1973 are described. The descriptions of the modulation-type ion trap and the retarding potential electron analyzer (trap) are given. Peculiarities of plasma measurements on oriented spacecrafts are considered. Results of laboratory tests of the devices and samples of primary results of onboard measurements in space are presented.

I. Techniques and devices

1. Experiment tasks and choosing of techniques

In the present paper experiments conducted on six spacecrafts launched toward the Mars in 1971 (Mars 2-3) and in 1973 (Mars 4-7) are described. On these spacecrafts almost identical devices were installed for the study of both ion and electron components of the solar wind (some difference between the 1973 and 1971 devices is outlined below). The main task of experiments was the study of characteristics of the near-Martian plasma which is necessary for the understanding of the interaction of Mars with the interplanetary medium. In addition, measurements conducted during the long-term flight from the Earth to the Mars and at orbits of Mars satellites allow to obtain statistically reach information on solar wind fluxes, velocities, densities, ion and electron temperatures, interplanetary shock waves, etc. It should be especially noted that for the choosing of the correct model of the solar wind (from a number of presently existing theories) it is necessary to know the radial heliocentric distribution of the electron temperature T_e in the solar wind. However, the available data on T_e are mainly obtained near the Earth's orbit [1].

Up to the present measurements of solar wind characteristics were performed by means of devices of two main types: charged particle traps (for example, [2-5]) and electrostatic analyzers (for example, [6-9]). In USA scientific literature the charged particle traps are sometimes named retarding potential analyzers [4] and Faraday cups [5]. The devices of each type has both advantages and defects. Curved (cylindrical or spherical) electrostatic analyzers give one the possibility to apply for the analysis of charged particles of the given energy, much more lower voltages (by several times) than those in charged particle traps. The angular diagram (the dependence of a current on the angle between the particle velocity and the normal to the aperture) of curved analyzers lied as a rule within several degrees. Electrostatic analyzers are broadly applied in USA on spacecrafts spinning around the axis inclined to the ecliptic plane by~60° or ~ 90° (the spacecraft of the series "Vela" [10] and "Pioner-6" [11] respectively). The narrow angular diagram of the devices enables one to determine with sufficient precision the direction of the arrival the charged particle flux and a high sampling rate of the telemetric system compared to the spacecraft spin period allows to measure the particle energy spectrum when variation of the orientation of the device is small (see, for example, [8]).

As spacecrafts under consideration were oriented to the Sun with the high accuracy (~ ±1) and the direction of arrival of solar wind fluxes can differ from that to the Sun by angle within ±10° [1], it is extremely difficult to determine the angle of arrival as well as the density and the integral flux of solar wind ions by using of device with the narrow angular diagram.

Charged particle traps may have angular diagrams (using suitable collimators) from several or even fractions of degree to several tens of degrees. This point played the main role in the choosing of the measurement technique at spacecrafts under consideration. A wide-angle modulation-type trap oriented to the Sun makes it possible (in spite of possible significant variations of angles of arrival θ) to determine the majority of characteristics of solar wind ions: the flux, the density, the velocity, the temperature, the α-particles content. Solar wind electrons characterized by a low anisotropy [8, 12] , by thermal velocities exceeding their bulk velocities and by energies close to those of photoelectrons and secondary electrons emitted from the spacecraft surface we prefer to study by means of electron traps. These traps were placed on the permanently shaded part of spacecrafts Mars and oriented in the antisolar direction. Considerations in favour of such a choice are presented in detailes below.

Let us note that at same spacecrafts cylindrical electrostatic analyzers were installed by another group of experimentators for the study of the solar wind (in particular, of the ion component) [13, 14] .

Conception of plasma under investigation derived from the experimental results strongly depends on characteristics of the device and on the method by means of which they are taken into account during the experimental data processing. Therefore, one of main task of the present paper is to describe the devices used the results of their laboratory tests and the primary data obtained from the spacecrafts Mars 2-7. The technique of further data processing (some samples of primary data are given in this paper) and the interpretation of the results obtained will be given elsewhere, in particular, in [15].

2. Measurements of plasma ion component

Measurements of ion energy spectra in the solar wind were made by means of charged particle modulation-type traps on many spacecrafts (soviet spacecrafts Zond-2 [16], Venera-3 [17], Prognoz and Prognoz-2 [18, 19], american spacecrafts Pioneers [5, 20], Explorers [21, 22] and so on).

The modulation-type traps on spacecrafts of series Mars were mounted on the illuminated part of each spacecraft (see fig. 1a). The normal to the apperture coincided with the solar direction to within ±1°. The diagram of the trap is shown in fig. 2. Each energy spectrum was measured in 16 energy intervals. (Table 1).

Table 1

No. of interval	1	2	3	4	5	6	7	8
Width of energy interval (v)	0–40	40–70	70–103	103–200	200–332	332–500	500–700	700–932
No. of interval	9	10	11	12	13	14	15	16
Width of energy interval	932–1195	1190–1500	1500–1835	1845–2225	2225–2625	2600–3060	3010–3550	3550–4100

The modulating frequency is ~ 700 c. The measurement of one spectrum lasts 51 sec. The time interval between successive spectra is changeable and it may be 2, 10 and 20 minutes. In the selective amplifier of trap collector currents sensitive to the modulating frequency the phase detector circuit is used.

Some results of laboratory tests of modulation-type traps were presented in [23]. In modulation-type traps installed on spacecrafts Mars 2-7 the structure of the modulating grid and the distance between electrodes were changed and therefore dependences of registered currents on the ion energy and on the angle of arrival of ions relative to the axis of symmetry of the trap were also changed. In laboratory tests the traps were irradiated by quasimonoenergetic beams of Ar^+ ions with energies $\bar{E} \sim 1000$, 2000 and 3000 ev. The angle of arrival of ions θ varied within 0-45°. The energy dispersion of ions did not exceed 1.5%, the divergence of beams was $\sim 0.5^\circ$, the intensity inhomogenity of the beam was less than 0.6% within the trap aperture. In fig. 3 a volt-ampere and angular characteristics of a modulation-type trap are presented which were obtained with the use of Ar^+ ion fluxes with the energy 1950 ev.

The characteristics of the trap, amplifier and telemetric system enable one to measure by means of this device ion fluxes over the range $10^6 - 10^{10}$ cm^{-2} sec^{-1} in each energy interval.

The determination of parameters of ion fluxes in the solar wind is realized by the comparison of measured ion spectra with calculated ones. Calculations of spectra were conducted with taking into account of laboratory characteristics of traps under the assumption that the mixture of protons and α-particles has (in the coordinate system related to the solar wind) Maxwellian velocity distribution at different combinations of the solar wind bulk velocity V, the proton temperature T_p and α--particle temperature T_α.

3. Measurements of plasma electron component

Before the description of measurements conducted on spacecrafts Mars 2-7 it is necessary to outline some peculiarities of measurements of solar wind electrons performed earlier by other authors and obtained results.

Knowledge of characteristics of solar wind electrons is of great importance. One of main plasma parameters from the point of view of instabilities development β (the ratio of the thermal energy in volume unit to magnetic one) in the solar wind is primarily determined by the electron temperature T_e, which as a rule is significantly higher than the proton temperature T_p. A number of experiments on solar wind electrons is not great. They include measurements by means of electrostatic analyzers (Pioner -6 [24], Vela-4 [8]) and by means of the electron trap (Explorer-35 [4]). There are no publications about measurements of solar wind characteristics on large distances from the Earth's orbit.

Some peculiarities of measurements in the solar wind by means of the electron trap with planar geometry on the electrically charged spacecraft (with the energy analysis of electrons by the method of retarding potentials) were considered by E.Wipple and L. Parker in [12, 25]. In [12] results of measurements in the solar wind by means of the electron trap on the satellite OGO-1 in 1964 are also analyzed. Some conclusions drawn in these papers one can resume in the following way:

1. The electron trap on the spacecraft flied in the space registers in addition to electrons of environmental medium photoelectrons including emitted inside the trap by the ultraviolet solar radiation and secondary electrons.

2. Photoelectrons and secondary electrons make a significant contribution to a collector current (forming a bend on a volt-ampere characteristic) at 2-6 volts from the zero retarding potential on the analyzing grid relative to the spacecraft body.

3. The retardation curve can be interpreted as a result of influence of two components of the electron gas: of a "cold" component with the temperature 2-5 ev and the density of the order of hundreds particles in cm^{-3}, and of a "hot" component with the temperature of the order of some tens ev and the density about several particles in cm^{-3}. This "hot" component consists of solar wind electrons.

In processing of results of measurements of T_e by Montgomery et al. (Vela-4 [8]) the descending branch of the distribution function is used from the energy ~ 16 ev apparently in order to exclude the influence upon it of photo- and secondary electrons from the spacecraft surface. In the same paper the possibility of registration of solar wind electrons beginning from mentioned energies on the shaded part of the spacecraft, is experimentally shown. In this case the registered electron flux which comes from the antisolar direction is about twice less than that coming from the solar one. The shape of the distribution function (except peculiarities in "superthermal tails") is practically the same in both directions. The location of the electron trap on the shaded part of the spacecraft [8] allows one to avoid completely the registration of photoelectrons emitted inside the trap and from the closest to the trap parts of the spacecraft surface and gives one the possibility to perform sufficiently correct measurements of T_e . In fig. 1b the location of the trap on the shaded part of the spacecraft is shown; minimum distance from the trap to the terminator exceeds 10^2 cm.

Let us show that in the determination of T_e one can exclude the dependence of photoelectrons coming from the illuminated surface of spacecraft using only a part of the retardation curve corresponding to values of retarding potentials more than a certain threshold (see, for example, [8, 12]). The value of this threshold is closely related to that of the spacecraft potential which in turn is primarily determined by the flux of electrons from the environmental medium and the photoemission current value. The most complete results of the study of photoemission are given by Grard 26 , which includes the data of careful laboratory measurements of the photoeffect from different materiels and of rocket solar ultraviolet radiation spectrum measurements. In [26] it is shown that the distribution function of photoelectrons emitted by the solar ultraviolet radiation peaks at values of energies 0.8 - 1.5 ev depending upon a surface material; the mean value of a photoelectron energy is 1.2-2.2 ev. A current of photoelectrpns with energies $>$3-6 ev and $>$10 ev are less than the total current of the electron photoemission by an order of magnitude and two orders of magnitudes respectively.

The flux of electrons from an environmental medium $5 \cdot 10^8$ $cm^{-2}sec^{-1}$ (corresponding to the solar wind electron flux at $T_e \sim 1.5 \cdot 10^5$ °K and $n_e \sim 8$ cm^{-3}) causes the spacecraft potential $\varphi_o \sim +3$ v in case of a flat body and $\varphi_o \sim +2$V in case of a spherical one [26] . This conclusion is in agreement with Whipple's and Parker's data [12] , although it contrasts with

Serbu's data [4] (according to [4] φ_0 of Explorer-35 was ~ -1.5 v). Using solutions of the task about a particle motion in a field of radial forces varying as $1/r^2$ (see, for example, [27]) one can show that electrons emitted from the surface of a spherical body with the kinetic energy $> e\varphi_0$ does not return on the surface. If it is the case for bodies of a more complicated formes, all photoelectrons with energies exceeding $e\varphi_0 \simeq$ 3-5 ev do not return on the spacecraft and so should not be registered by a detector on the shaded part of the spacecraft. One must bear in mind that the current of photoelectrons registered on the shaded part of the spacecraft and of secondary electrons should reduce with increase of the distance from the spacecrafts terminator. Therefore it is desirable to place the electron trap at the maximum distance from the shadow-light boundary. In our case, as it was mentioned above, this distance is more than 10^2 cm. Taking into account that the trap is remoted from the spacecraft terminator (see fig. 1b) one can suggest that the significant part of photo- and secondary electrons from the illuminated part of the spacecraft which could reach the trap should have considerable components of velocities parallel to the trap aperture. Therefore the trap is designed in such a way that it is completely insensitive to electrons with slightly sloping trajectories (with angles of arrival $> 40^\circ$ relatively to the trap axis).

The appearance of the electron trap is shown in Fig. 4a. In Fig. 4b the schematic electrical diagram is given with basic geometrical dimensions. The trap axis is directed in antisolar direction to within $\pm 1^\circ$. As one can see from Fig. 4b the electron trap has four electrodes: the analyzing interspace is formed by two spherical grids (3-4), and two electrically joint planar grides(5) serve as an electrostatic screen. The total optical transparency of the system of grids in the trap is 0.6. The collector(6) is made in the form of a planar electrode with the "honeycomb" mouthpiece. All electrodes of the trap, its inside surface and gills(2) (which are designed to reduce a number of electrons reflected from walls of the trap) are gold-plated.

Laboratory studies of trap characteristics were conducted in a vacuum chamber. The trap was irradiated by quasimonoenergetic beams of Ar^+ ions with different beam energies $\bar{E}$ (14,6 ev; 48.8 ev, 100 ev, 525 ev). An angle between the direction of the ion motion in a beam and the trap axis varied from 0° to 40°. The use of heavy ions allows to exclude errors associated with curving of electron trajectories in scaterring magnetic fields and in the geomagnetic field. Results of laboratory measurements are presented in fig. 5. In fig. 5a the dependence is shown of the trap collector current on a dimensionless value of the ratio of the retarding potential on the analyzing grid to the energy of the beam of Ar^+ ions. Values of currents are normalized to that at zero retarding potential. The curve given in fig. 5a is practically independent of the angle of the incidence of ions on the trap θ . In fig. 5b angular characteristics of traps are shown which were obtained at abovementioned energies of ions normalized to the unit at zero angle of the incidence of ions on the trap. Angularcharacteristics measured in such a way are slightly dependent upon values of the retarding potential φ_3 on analyzing grid (φ_3 was constant when each special characteristic was measured) and the energy of the ion beam.

The duration of measuring of one electron spectrum and the time interval between measurements by the electron trap are the same as by the modulation-type trap. These values were mentioned above.

On spacecrafts Mars 2-3 each retardation curve was taken over 14 steps of the retarding potential which were choosen according to four programs depending upon values of T_e (see Table 2).

Table 2

No. of step / No. of program	1	2	3	4	5	6	7
I	0	3.15	4.55	6	7.6	9.3	10.5
II	0	5	9.6	12.6	16.8	22	24
III	0	9.8	11.8	15.5	19.5	24.5	28.5
IV	0	9.8	12.3	16.7	19.6	24.9	28.6

No. of step / No. of program	8	9	10	11	12	13	14
I	12.4	14	15.3	16.8	18	20	21
II	28	32	36	39	43	47	52
III	31	42	53	66	77	90	103
IV	31	51	70	89	170	270	400

The full-scale range of the amplifier of the collector current (from 5.5×10^{-13}a to 1.55×10^{-9}a) was divided into three linear subranges. When the collector current reached certain values the automatic switching of subranges occured. The instrument sensitivity was 0.4×10^{6} cm^{-2}sec^{-1}ster^{-1} for the isotropic electron flux (with taking into account the characteristics of the trap, amplifier and telemetry system).

As the curcuit for the automatic choice of programs on

Mars 2-3 sometimes operated unsufficiently efficient retardation curves on Mars 4-7 were taken according to the only standard program containing 16 steps of retarding potential (see Table 3).

Table 3

No. of step	1	2	3	4	5	6	7	8
Retarding potential (v)	0	2	4	7	10	14	18	23
No. of step	9	10	11	12	13	14	15	16
Retarding potential (v)	23	35	50	75	100	150	200	300

The duration of measuring of one spectrum and time intervals between measurements are the same as on spacecrafts Mars 2-3. The sensitivity of the amplifier increased up to some degree compared to Mars 2-3 (to $3,33 \times 10^{-13}$a). The sensitivity to the isotropic electron flux increased up to $0,8 \times 10^{6}$ $cm^{-2}sec^{-1}ster^{-1}$.

4. Samples of primary results of measurements and some conclusions

In fig. 6a, b typical samples are given of primary differential spectra of solar wind ions which were obtained on spacecrafts Mars-6 and Mars-7 on September, 1973. Numbers of energy intervals corresponding to Table 1 are shown on the axis of abscissae. The broad spectrum in fig. 6a corresponds to the magnetosheath of the Earth. The spectrum presented in fig. 6b is obtained close to the Earth's orbit in the undisturbed solar wind. In the right part of this spectrum one can clearly seen the peak caused by α -particles of the solar wind. The further processing of similar spectra is made by the method mentioned in section 2 of this paper.

In fig. 7 electron spectra are shown which are obtained on spacecrafts of series Mars. In [15] the expression is derived for the collector current created by electrons from the environmental space with the isotropic Maxwellian distribution function for the electron trap described in the previous section. Smooth curves in fig. 7 correspond to values of currents calculated theoretically according to [15] with taking into account of laboratory characteristics of the trap given above. The majority of experimental points satisfactorily fall on theoretical curves. However there are essential differences from calculated curves near the zero retarding potential. According to results by Whipple and Parker [12] shaded regions of current values near the zero retarding potential can be interpreted as caused by secondary electrons and photoelectrons from the illuminated spacecraft surface. As compared to [12] the exceeding of I_{max} over its value determined by electrons in the environmental medium is small. This can be explained in our opinion by following factors. First, the absence of a photoemission and the weakening of registration of secondary electron inside the trap. Second, the trap is significantly distant from the spacecraft terminator. Third, the trap has a comparatively narrow angular diagram and does not register electrons with inflow angles $> 40^\circ$ relative to the trap axis. In [15] additional considerations are given and according to them one can reliably determine T_e from results of these experiments. It is only necessary to exclude parts of volt-ampere characteristics near the zero retarding potential.

The method of the determination of ion energy spectra in the interplanetary plasma by means of the modulation-type trap was repeatedly tested previously. Spectra presented in fig. 6 are similar to those obtained in such experiments (there is a difference, however, from early soviet experiments [16] in a number of energy ranges).

Retarding curves of interplanetary plasma electrons similar to those given in fig. 7 do not differ on principle from corresponding curves obtained in the USA experiments with electron traps [12] . Nevertheless they have some peculiarities owing to effective actions taken on spacecrafts Mars 2-7 to weaken the influence of photo- and secondary electrons from the spacecraft and the inside of the trap.

As it was mentioned above a detailed description of all obtained results and their interpretation will be published elsewhere.

Figure captions

Fig. 1 a) The position of the ion trap on the spacecrafts launched toward the Mars in 1971

b) The position of the electron trap on the same spacecrafts.

Fig. 2 The scheme of the ion modulation-type trap

Fig. 3 a) Volt-ampere characteristics of the ion modulating-type trap according to the data of laboratory measurements

b) An angular characteristic of the same trap according to the data of laboratory measurements

Fig. 4 a) The appearance of the electron trap

b) The diagram of the electron trap

Fig. [illegible] a) A volt-ampere characteristic of the electron trap (result of laboratory measurements)

b) An angular characteristic of the electron trap (result of laboratory measurements)

Fig. 6 Samples of ion spectra obtained during the flights of the spacecrafts to Mars

a) in the Earth's magnetosheath

b) in the solar wind

Fig. 7 Samples of electron spectra obtained during the flights of the spacecrafts to Mars

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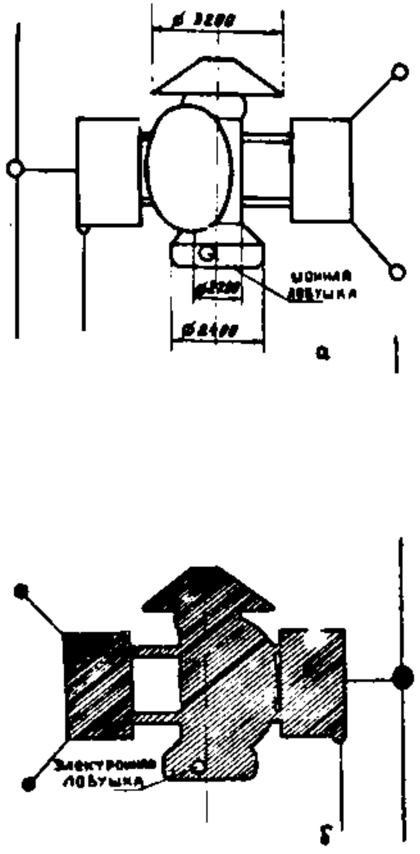

Fig. 1

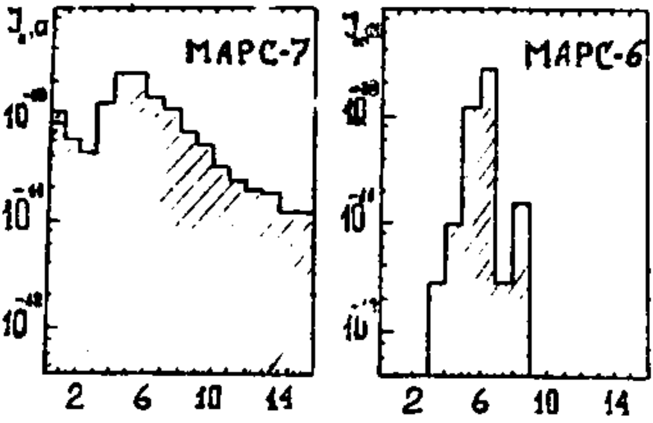
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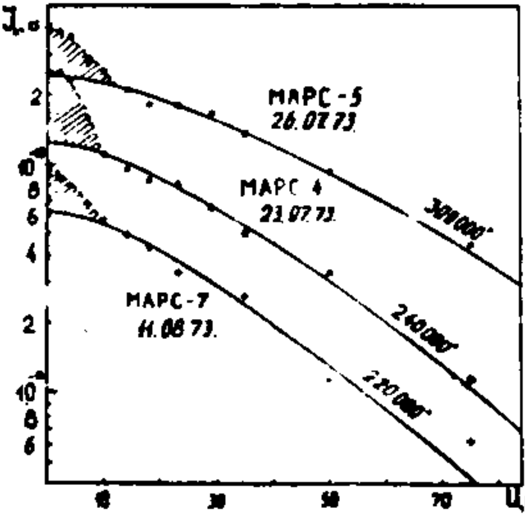
Fig. 6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