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Observations of Multicomponent Distribution Function of Ions on the *Interball/Tail Probe* Satellite

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Abstract—Ion distributions in the inner magnetosphere were measured with the CORALL instrument onboard the *Interball/Tail Probe* satellite. During the first year of observations, a multicomponent distribution of ions was observed that included a cold core and a hot population in the form of one or two spherical layers at the background of an even hotter tail of the distribution. Preliminary results show such distribution to be observed at a distance of ~(2–10)R_E from the Earth, near the ecliptic plane. These events are projected into the region of invariant latitudes (ILAT) ~60°–70° at different values of the magnetic local time (MLT). The distributions measured have some features that have earlier been observed by other spacecraft (for example, the "ion gaps" which were observed onboard the *Interball/Auroral Probe* satellite with the ion energy spectrometer ION), but, in the case of *Tail Probe* they are observed at larger distances.

1. INTRODUCTION

In the literature, there are separate experimental data about the decrease (gap) of energy spectra in the range from a few hundred to several thousand electron-volts for ion fluxes in the inner (2–7)R_E near-equatorial magnetosphere [2, 4, 6, 7, 10]. These observations, however, were rather scarce, and all of them were made at low- and middle-apogee spacecraft: geosynchronous, *AMPTE*, *Akebono*, and *Interball/Auroral Probe*, respectively. Therefore, observations of this phenomenon by the high-apogee satellite *Interball/Tail Probe* with an apogee of ~30R_E would allow this effect to be observed at larger distances from the Earth. In addition to studying separate energy spectra of ions, the present paper analyzes peculiarities of the three-dimensional distribution function of ions. This information is extremely important when the phenomenon described is theoretically explained or numerically simulated.

2. TECHNIQUE OF MEASUREMENTS

The *Tail Probe* satellite of the INTERBALL project was launched on August 3, 1995 into an orbit with the following parameters: $H_a \approx 184\,000$ km, $H_p \approx 900$ km, inclination ≈65°, and period $T \approx 92$ h. After the launch, the height of perigee that is located in the Earth's southern hemisphere increased steadily and reached a maximum of ~4R_E in the beginning of 1998. After that, it began to decrease. Thus, the orbit allows measurements of the inner magnetosphere to be made starting from an altitude of at least ~4R_E (from ~2R_E during the first year of the satellite's operation). The spin axis of the satellite did not deviate from the direction to the Sun by an angle of more than 10°.

The scientific payload of the project is described in [1, 11]. Basically, our analysis utilized the data of the energy–angle ion spectrometer CORALL [12, 13] and the data of magnetometers FM-3 and MIF-M [3, 8]. For a period of 4 s, the CORALL instrument measures energy spectra of ions in the energy range 30 eV–25 keV in five directions lying in a plane that contains the satellite's spin axis. For the time of satellite revolution about its spin axis (2 min), the instrument scans a complete 3-D distribution function (DF) of ions. In the present paper, we analyze both energy spectrograms measured by individual detectors and 2-D cross sections of 3-D ion DF over velocities. In order to make the analysis using DF, the intercalibration of five channels of the CORALL instrument was completed.

The CORALL instrument is mounted immediately at the outer side of the instrument compartment of the satellite and has no sufficiently reliable protection against penetrating radiation. Therefore, at the a priori dangerous time intervals, when, according to model calculations, the satellite should be located in the most hazardous (for instrumentation) parts of the radiation belt, CORALL was switched off to avoid failures due to radiation damage. Actually, this interval was broadened by 30–60 min in both directions for better reliability. Therefore, near the perigee, the data always have gaps of a duration of about 3 h. This was taken into account when making statistical analysis of phenomena, because an event under consideration could be missed in the records due to the instrument being switched off at the intervals discussed.

3. RESULTS

As an example, let us consider the measurements carried out on January 9, 1996 at 08:00–11:00 UT under magnetically quiet conditions ($K_p = 0$, $D_{st} = -1$ nT). Figure 1 presents observations of the ion energy spectra in

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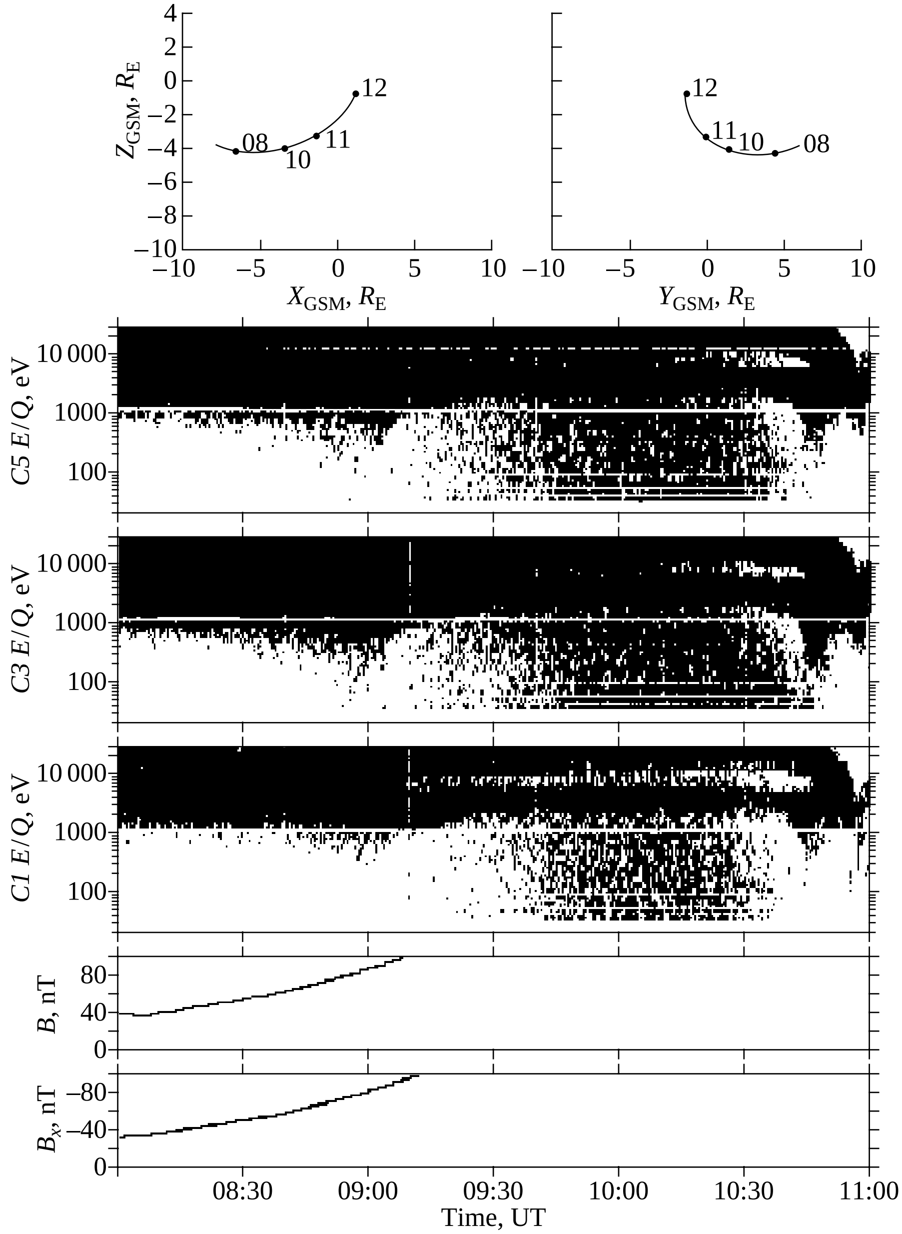

Fig. 1. Observations of plasma and magnetic field onboard the *Interball/Tail Probe* satellite. The upper panels represent the satellite's trajectory; dynamic spectrograms of ions in three different directions: away from the Sun (*C1*), toward the Sun (*C5*), and perpendicular to the Sun–Earth line, are presented at the middle panels; and the lower panels give the magnetic field magnitude *B* and B_x component.

three directions and the magnetic field, as well as two projections of the satellite's orbit. At first, the satellite was located in the dusk sector of the magnetosphere ($Y_{GSM} > 0$) at a distance of ~$6R_E$ and was moving to the Earth and the midnight meridian. At 11:00, the satellite has crossed the midnight meridian at X ~ 2 and Z_{GSM} ~ $3R_E$. The dynamic spectrograms presented were measured by the channels *C1* (nearest to the spin axis of the satellite and the sunward direction), *C3* (perpendicular to the spin axis), and *C5* (nearest to the satellite's spin axis and the antisunward direction). When analyzing Fig. 1, one should take into account that the raw data are presented, without allowance made for relative sensitivity of channels that comprised *C1/C5* ~ 0.54 and *C3/C5* ~ 1.28; i.e., the sensitivity of the *C1* channel was approximately twice lower than that of channel *C5*. Ion measurements with the CORALL instrument show the satellite to be initially in the plasma sheet, because the hot rarefied (T_p ~ 6 keV and n_p ~ 0.8 cm^{-3}) isotropic plasma was recorded, which is typical for the plasma sheet [5, 13]. At ~08:15 UT, the maximum of energy spectra begins to decrease from ~10 keV down to ~2 keV, and at ~08:45 the "splitting" of spectra occurs, at first weakly and then, at ~09:00, very clear. They

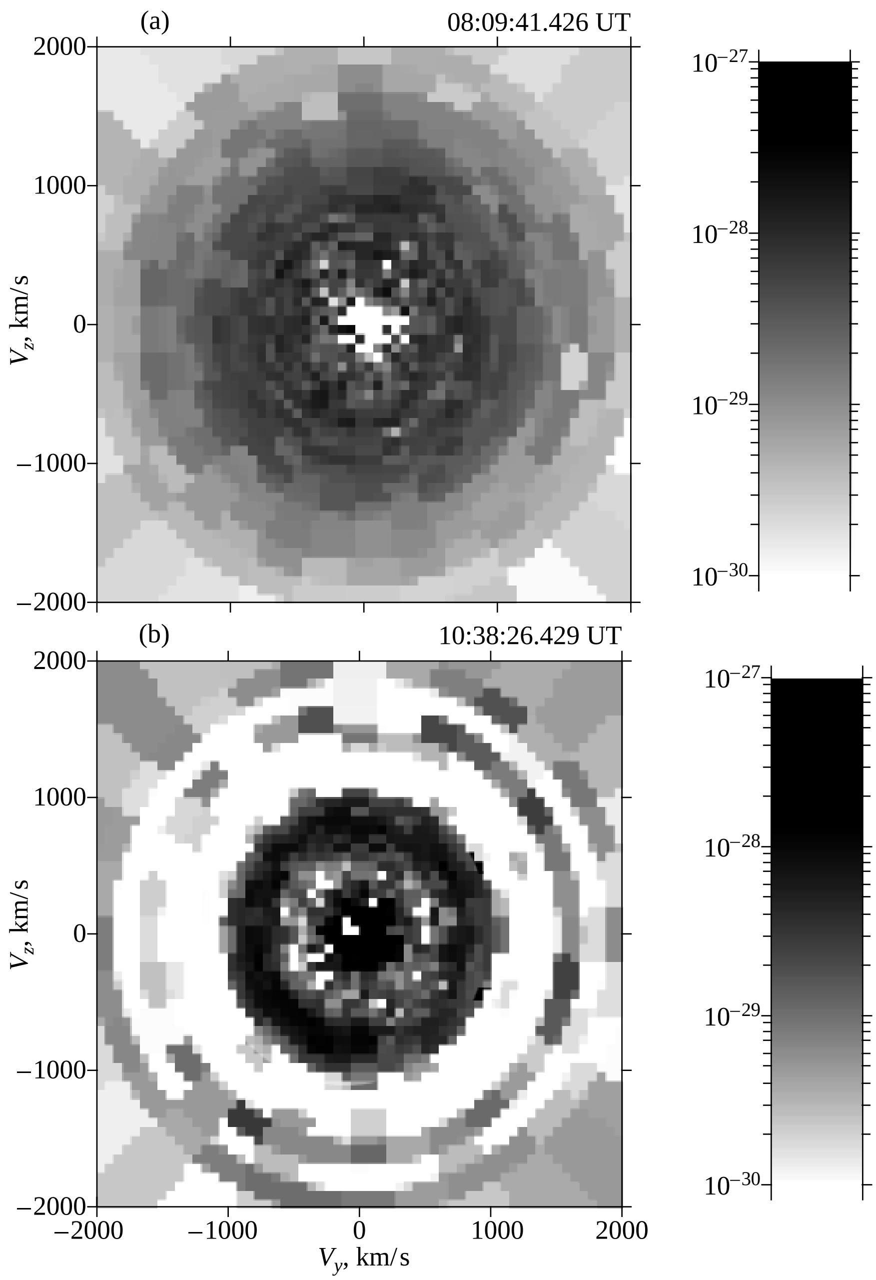

Fig. 2. Cross sections of the ion distribution function in (a) the plasma sheet and in (b) the region of multicomponent plasma.

now have two components with a maxima of ~2 and ≥10 keV, respectively, and a large gap in between. This splitting with a gap has been observed up to ~10:45. The general increase of noise at all energies in the period 09:30–10:30 is related to a passage of the satellite through the low-energy part of the Earth's radiation belt and to a corresponding effect of the penetrating radiation on sensitive elements of the instrument.

Cross sections of the ion distribution function shown in Fig. 2 were measured in the plasma sheet at 08:09:41 (a) and in the period of ion gap at 10:38:26 (b). They allow one to clearly demonstrate the DF difference in these regions. In the first case, DF is of a bell-like shape with a maximum in the center (in the very center of DF, $|V_p| \leq 200$ km/s, there are no measurements) and a gentle monotonous decrease to $|V_p| \sim 2000$ km/s. The second DF also has a cold ($T_p \sim 0.2$ keV) maximum at $|V_p| \leq 400$ km/s, apparently more intense than in Fig. 2a, but two gaps of an order of magnitude in DF value are observed further in the intervals $400 \leq |V_p| \leq 700$ km/s and $900 \leq |V_p| \leq 1300$ km/s. One can not also exclude the possibility of a third gap in the interval $1600 \leq |V_p| \leq 1800$ km/s. Cross sections in mutually perpendicular planes show that these gaps (or DF plasma population) have a form of narrow spherical layers.

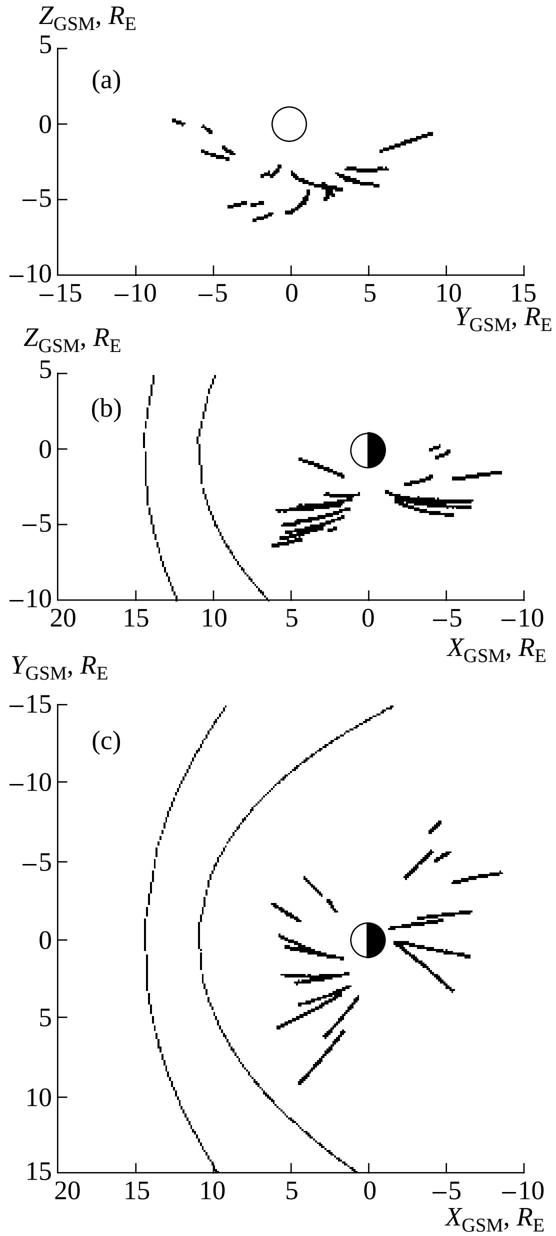

Fig. 3. Projections of the satellite orbit in the GSM system of coordinates for the moments of observing the multicomponent plasma.

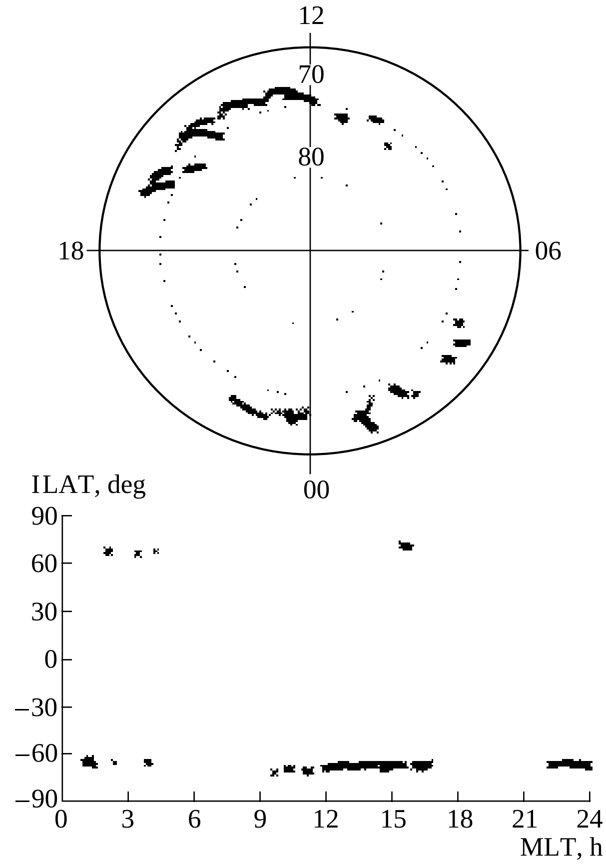

Fig. 4. The same as in Fig. 3 in the ILAT–MLT coordinate system (invariant latitude–magnetic local time).

About 100 satellite passages through the perigee region ($|X| \leq 12R_E$) have been analyzed for the first year of operation of the CORALL instrument (September 1995–September 1996). The statistic of those observations, in which multicomponent distribution functions were observed, is presented in Fig. 3 in the form of three projections of the satellite trajectory in the orthogonal GSM system. The same bits of trajectories projected along the model magnetic field into the MLT–ILAT coordinate system are shown in Fig. 4. One can see that all these events are located at distances 2–10R_E from the Earth, a bit lower than the geomagnetic equator plane (this is due to a constraint imposed by the orbit type), and they are observed at different MLT. It is important to note that all events are projected into a sufficiently narrow interval of ILAT (60°–70°). The analysis of geomagnetic activity in the period of observing these effects showed that the magnetosphere was fairly quiet: $K_p \leq 3+$ (mean 1+) and $D_{st} \geq -42$ nT (mean –8 nT).

4. DISCUSSION AND CONCLUSIONS

Analyzing the results of observations (for the period September 1995–September 1996) of plasma and magnetic field onboard the *Interball/Tail Probe* satellite in the inner magnetosphere at distances 2–10R_E from the Earth, one can make the following conclusions:

regions are discovered where the three-dimensional distribution function of ions contains a cold (<1 keV) core and one or two more energetic (2–15 keV) populations have a form of spherical layers (i.e., almost monoenergetic and isotropic distributions);

these phenomena are observed under magnetically quiet conditions at distances of 2–10R_E and are projected to invariant latitudes ILAT ~60°–70° at different values of magnetic local time MLT;

the peculiarities observed in ion energy spectra and the position of ion gaps on them are close in their characteristics to those observed earlier at lesser distances of 2–7R_E onboard other spacecraft [2, 4, 7, 10];

qualitatively, the results of our observations coincide with predictions of some model calculations for the dynamics of ion populations as a function of ion energy, the place of injection, and magnetospheric conditions (see, for example, [2, 4, 7, 10] and references therein). However, further quantitative examination is needed, especially as far as explanation of simultaneous observation of several ion populations of the distribution function and their shape is concerned. The shape of distributions can give additional arguments in favor of one or another physical mechanism responsible for ion dynamics in the inner magnetosphere.

The results obtained are preliminary in nature and will be checked using a larger statistic of observations both on the *Interball/Tail Probe* satellite and aboard other spacecraft, primarily *Interball/Auroral Probe*. Simultaneous observations by several spacecraft allow one to investigate in detail the geometry and dynamics of the class of phenomena described.

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REFERENCES

1. Galeev, A.A., Galperin, Yu.I., and Zelenyi, L.M., The Project INTERBALL to Study Solar–Terrestrial Physics, *Kosm. Issled.*, 1996, vol. 34, no. 4, pp. 339–362.
2. Kistler, L.M., Ipavich, F.M., Hamilton, D.C., and Gloeckler, G., Energy Spectra of the Major Ion Species in the Ring Current during Geomagnetic Storms, *J. Geophys. Res.*, 1989, vol. 94, p. 3579.
3. Klimov, S., Romanov, S., Amata, E., *et al.*, ASPI Experiment: Measurements of Fields and Waves onboard the INTERBALL-TAIL Mission, in *INTERBALL: Mission and Payload*, Toulouse: RKA-IKI-CNES, 1995, p. 120.
4. Kovrazhkin, R.A., Sauvaud, J.-A., and Delcourt, D.C., INTERBALL/Auroral Observations of 0.1–12 keV Ion Gaps in the Diffuse Auroral Zone, *Ann. Geophys.*, 1999, vol. 17, p. 734.
5. Lui, A.T.Y., Road Map to Magnetotail Domains, in *Magnetotail Physics*, Lui, A.T.Y., Ed., Baltimore and London: Johns Hopkins University, 1987, p. 3.
6. McIlwain, C.E., Plasma Convection in the Vicinity of Geosynchronous Orbit, in *Earth's Magnetospheric Processes*, McCormac, B.M., Ed., Dordrecht: D. Reidel, 1972, p. 268.
7. McIlwain, C.E., A K_p Dependent Equatorial Electric Field Model, *Adv. Space Res.*, 1992, vol. 6, p. 187.
8. Nozdrachev, M.N., Styazhkin, V.A., Zarutsky, A.A., *et al.*, Magnetic Field Measurements onboard the INTERBALL TAIL Spacecraft: The FM-31 Instrument, in *INTERBALL: Mission and Payload*, Toulouse: RKA-IKI-CNES, 1995, p. 228.
9. Prokhorenko, V., Mission Analysis for the INTERBALL Project. Prelaunch Orbit Selection and Long-Term Experiments Planning, in *INTERBALL: Mission and Payload*, Toulouse: RKA-IKI-CNES, 1995, p. 46.
10. Shirai, H., Maezawa, K., Fujimoto, M., *et al.*, Monoenergetic Ion Drop-off in the Inner Magnetosphere, *J. Geophys. Res.*, 1997, vol. 102, p. 19873.
11. Yermolaev, Yu.I., Scientific Program of Solar and Solar Wind Observations: INTERBALL and Relict-2 Missions, *Proc. of the Third SOHO Workshop, Estes Park, USA*, ESA, 1994, p. 441.
12. Yermolaev, Yu.I., Fedorov, A.O., Vaisberg, O.L., *et al.*, Ion Distribution Dynamics near the Earth's Bow Shock: First Measurements with 2-D Ion Energy Spectrometer CORALL on INTERBALL/Tail Probe Satellite, *Ann. Geophys.*, 1997, vol. 15, p. 533.
13. Yermolaev, Yu.I., Observations of the Plasma Sheet: INTERBALL Project, *Kosm. Issled.*, 1998, vol. 36, no. 3, p. 273.