PLASMASPHERE AND ITS INTERACTION WITH THE RING CURRENT*

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Abstract. In the last few years (after 1976) new instruments have been used for plasmaspheric studies ('mutual-impedance' probe, ion energy-mass spectrometers) which have led to new results. The existence in the plasmasphere of previously unknown ions (He^{2+}, O^{2+}) was revealed and the pitch-angle distributions of ions with energies 10–20 eY were measured. New measurements confirmed the existence of a 'hot' ('warm') zone in the outer plasmasphere and of a midday-midnight asymmetry of the plasmasphere. The source of outer plasmasphere heating is apparently the ring-current decay; electrons are heated less than ions. The plasmasphere is not only the medium of ring current decay, but it appears that it is one of the ring-current ion sources.

1. Introduction

Satellite measurements of plasma ion and electron components are one of the main sources of our knowledge about the plasmasphere. They belong to the most complicated physical experiments in space. Measurements of the electron component of the plasma by the Langmuir probe method, easily realizable in the ionosphere, are impossible in the plasmasphere at low electron-number densities n_e due to the satellite-emitted photoelectrons. It is easier to measure ions with energies of the order of less than 1 eV or several eV than electrons, but ion measurements are also rather complicated, due to the necessity of taking into account the satellite potential Φ_{sat}.

These difficulties may partially explain why – though the plasmasphere was discovered more than 20 years ago – the results from earlier papers have sometimes been questioned. Late in 1979, for instance, Horowitz and Chappell (1979) stated that at $L < 3$ no information is available about the ion temperature T_i in the plasmasphere region with $L \leq 3$ (see Figure 1), despite the measurements made from the OGO-5 and Prognoz satellites by Serbu and Maier (1970), and Bezrukikh and Gringauz (1976), which yielded the T_i-distribution in the plasmasphere. From the point of view of plasmasphere studies, the period of the IMS, which started in 1976 is interesting since, along with the earlier used on-board instruments (ion traps, retarding-potential analyzers, ion mass-spectrometers), new types of instruments are now used: the so-called 'mutual-impedance probe' (Décréau *et al.*, 1982), which makes it possible to study the electron component of the plasma, including the plasmapause region; and the instruments which may be defined as 'hybrid-devices', as they combine the properties of the retarding-potential ion analyzer, electrostatic analyzer and mass-spectrometer. They also allow us to assess the energy and angular spectra of each type of ion which populate

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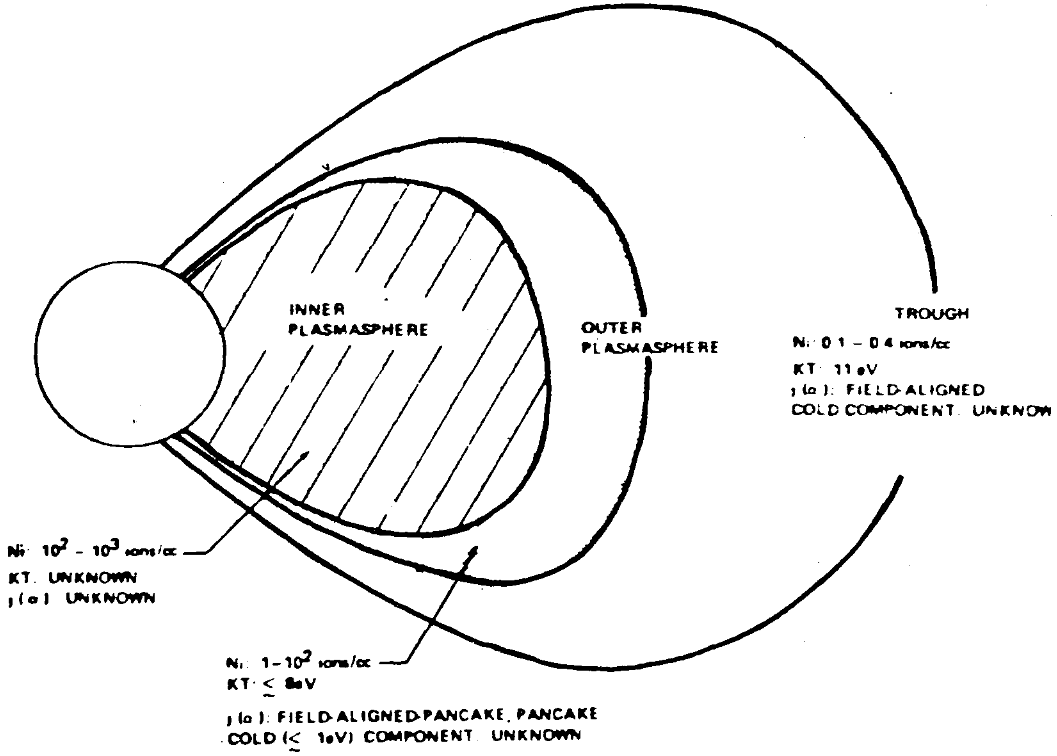

Fig. 1. Ion temperature T_i distribution in the plasmasphere according to Horowitz and Chappell (1979).

the plasmasphere (Geiss *et al.*, 1978; Baugher *et al.*, 1980; Chappell *et al.*, 1981). In addition to earlier collected data on ion masses, number density n_i and temperature T_i, the satellites have now been providing data about the pitch-angle distribution of the ions of each mass. The future opens up new possibilities for investigating the dynamics of plasmaspheric particles, processes of filling and depleting of magnetic tubes in the plasmasphere and for revealing the origin of plasmaspheric ions and mechanisms by which the plasmasphere is linked to other regions of the magnetosphere.

It does not mean that simpler instruments for studying the plasmasphere are not useful. Since the first ion mass-spectrometer measurements in the plasmasphere (Taylor *et al.*, 1966), it is known that the plasmasphere mainly consists of protons; latter measurements have not changed this result. Hence, measurements with 'simple' retarding-potential analyzers yield results mostly concerning protons and may be useful for prolonged, continuous measurements of large-scale plasmaspheric features (the fewer the number of 'modes' or various operation regimes the instrument has, the more intercomparable are the results it may provide).

In this paper we try to give a brief summary of the results of recent plasmasphere studies (i.e., since 1976) with emphasis on the results related to the temperatures of charged particles in the plasmasphere, associated with the ring-current interaction with the plasmasphere.

2. Density, chemical composition and pitch-angles of plasmasphere ions

Electron-number-density (n_e) distributions in the outer plasmasphere in the range $1 < n_e < 70\ \mathrm{cm}^{-3}$ were obtained by the 'mutual impedance' technique aboard the GEOS-1 satellite (Décréau *et al.*, 1982). This technique, which belongs to the category of active wave techniques, was used for the first time in the plasmasphere. This GEOS-1 instrument is less sensitive to photo electrons emitted from the satellite than other electron-measuring devices.

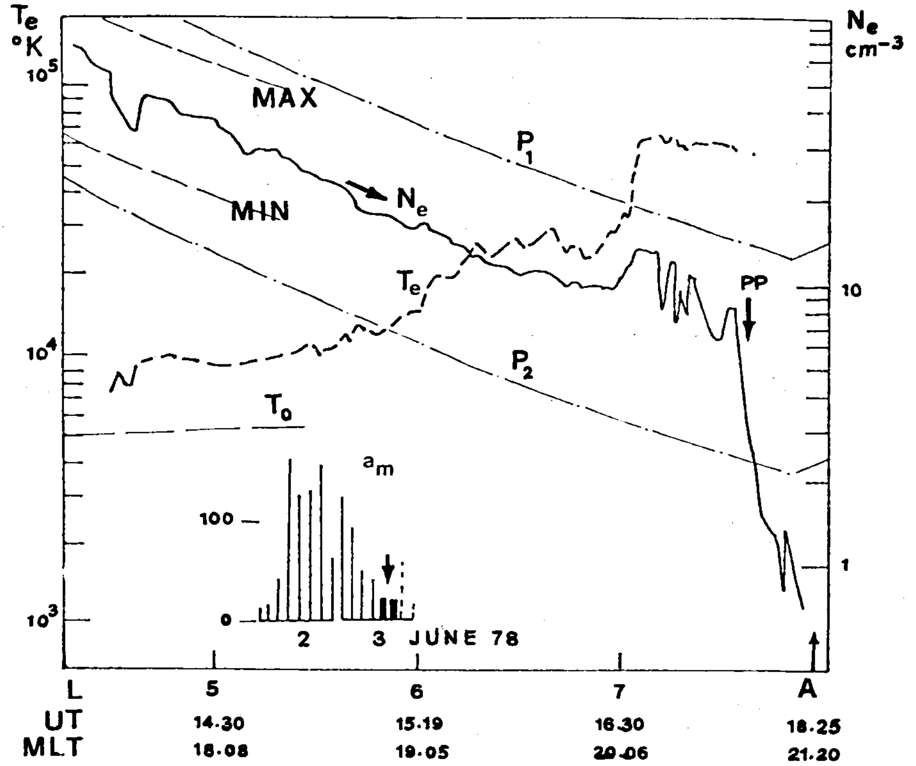

Fig. 2. Example of n_e (L) and T_e (L) distributions measured aboard GEOS-I by the 'mutual impedance probe' method (Décréau *et al.*, 1982).

Figure 2 shows an example of the distributions of n_e and T_e (Décréau *et al.*, 1982) measured on 3 June, 1978 in the dusk sector of the plasmasphere (MLT ~ 18^h to 21^h), *PP* is the plasmapause. At $L \sim 7$, T_e reaches $\sim 5 \times 10^4$ K. Below in Figure 2 is given the plot of the geomagnetic disturbances index a_m which shows that the data refer to the recovery phase of a strong magnetospheric storm. Décréau *et al.* compared data on the plasmapause location at various times MLT; they confirmed the presence of the well-known evening bulge and also pointed out the noon-midnight asymmetry of the plasmasphere first reported by Gringauz and Bezrukikh (1976). Let us note that the existence of the noon-midnight asymmetry with its height at noon considerably exceeding that at midnight, was also confirmed by the observations of whistlers (Carpenter, 1978) and by ion-number density n_i measurements with the retarding-potential method aboard the Prognoz-5 satellite (Gringauz *et al.*, 1981). A brief description of the latter results is given in Section 3.

An important experiment aboard the GEOS-1 satellite was the measurement of ion mass spectra (Geiss *et al.*, 1978). Together with the earlier observed protons and minor constituents (He^+ and O^+), O^{2+} and H^{2+} ions were also detected (it is difficult to differentiate them from D^+ since both ions have identical mass/charge ratios, M/q).

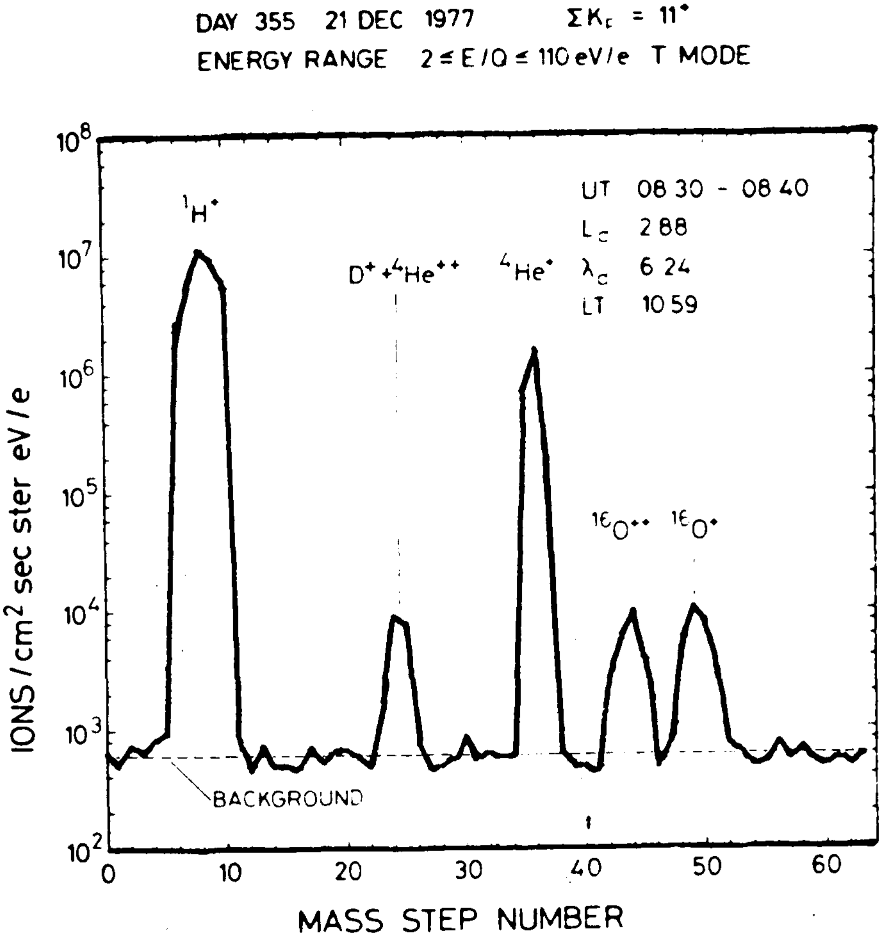

Fig. 3. Example of ion mass spectra in the plasmasphere from GEOS-1. The fluxes of O^{2+} and O^+ are practically the same (Geiss *et al.*, 1978).

The results were confirmed by measurements conducted with an ion energy mass-spectrometer aboard the ISEE-1 satellite (Baugher *et al.*, 1980). Figure 3 shows a sample of ion mass-spectra recorded in the equatorial plasmasphere at $L = 2.88$.

Geiss and Young (1980) attempted to explain the fact that the number density of O^{2+} ions reaches that of O^+ ions in the equatorial plane (at $L = 3$) while at midlatitudes, in the ionospheric F-region, their number-density ratio corresponds to $\sim 3 \times 10^{-3}$. They argue that neither photoionization of O^+-ions by the solar UV at high altitudes nor their impact ionization can explain such a high $n_{O^{2+}}/n_{O^+}$ ratio. The authors showed that under reasonable assumptions about the T_i distribution inside a flux tube for $L = 3$ and equinox conditions, the measured $n_{O^{2+}}$ values may be explained by thermal diffusion. The authors numerically integrated the time-dependent diffusion equation for O^{2+} along a flux tube inside the plasmasphere; in that case O^{2+} was regarded as a minor plasma component. These calculations were made under the assumption that at a height of about 500 km ($L = 3$) $T_i \sim 10^3$ K while at ~ 13000 km (in the equatorial plane) $T_i \sim 10^4$ K.

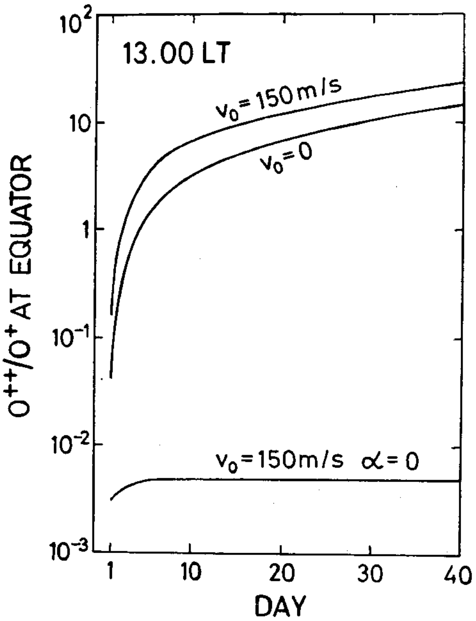

Fig. 4. The O^{2+}/O^+ ratio in the equatorial plane at $L = 3$; V is the bulk velocity of the basic gas; α is the thermal diffusion coefficient (Geiss and Jung, 1981).

Figure 4 summarizes the results of Geiss and Young's calculations. V_0 is the major gas motion velocity in the tube; α is the thermal diffusion coefficient. Figure 4 shows that the O^{2+} number density is a weak function of the major gas motion velocity, but decreases by 2 to 3 orders in the absence of thermal diffusion.

Ion pitch-angle distributions in the outer plasmasphere were first reported by Lennardson and Reasoner (1978) who used the data obtained with UCSD-electrostatic analyzers aboard the ATS-6 satellite, then by Horowitz and Chappell (1979), based on the data from the same instrument, then from the ISEE-1 by Horowitz *et al.* (1981a, b). It was found that in different periods, different kinds of ion pitch-angle distributions are observed: with the maximum along the geomagnetic field, with the maximum in the plane perpendicular to the magnetic field (a 'pancake' distribution), and a 'conical' distribution (with a sharp maximum in the pitch-angle range ~ 10 to 40°).

A pitch-angle distribution with the maximum along the magnetic field is natural for ions moving from the ionosphere when the earlier depleted field tube is being filled. The 'conical' distribution may develop either if after several 'bounces' a loss cone forms in the distribution due to the charge exchange, or if some other atmospheric losses take place, or when passing through the region where ions are accelerated perpendicular to the magnetic field – may be due to the electric fields of ULF ion-cyclotron waves (Horowitz *et al.*).

As to the ion pitch-angle distribution with the maximum in the plane perpendicular to the geomagnetic field, one should agree with Horowitz *et al.* (1981b) that the role of this distribution in magnetic flux-tube filling is not yet clear – it may also be the result of an ion-cyclotron wave interaction with ions.

To interpret unambiguously the data on pitch-angle distributions of charged particles in the outer plasmasphere further measurements are required and joint analyses with the results of simultaneous ULF measurements and total electron content in the flux tube (i.e., the tube accumulation process) using radiophysical methods (e.g., observations of whistlers or radio-waves emitted from a satellite with the measurement of group delay).

As far as we can judge from the available published data, the results of pitch-angle measurements of plasmasphere ions till now added little to the understanding of the physical processes in the plasmasphere and possibly even may have increased the number of unsolved problems.

3. Distribution of T_i in the Plasmasphere

Let us recall that Bezrukikh and Gringauz (1976), on the basis of observations from the Prognoz-satellite, suggested that we regard the plasmasphere as consisting of an 'inner' zone with relatively steady and 'cold' plasma ($T_i \lesssim 8 \times 10^3$ K), the boundary of which passes over the shell with $L \sim 3$, and of an outer zone with variable and 'hot' plasma when the ion temperature T_i near the plasmapause is $\sim 10^5$ K ($\sim$ 10 eV).

Later, other authors systematically observed ions with energy $E \sim 10$ eV in the outer zone of the plasmasphere from the ATS-6 (Lennardson and Reasoner, 1978; Horowitz and Chappell, 1979), and ISEE-1 satellites (Baugher *et al.*, 1980; Horowitz *et al.*, 1981). In the opinion of the GEOS-1 experimenters (Décréau *et al.*, 1982) the electron temperatures T_e (measured by the mutual impedance technique) are in qualitative agreement with the existence of the plasmasphere's hot zone (though T_e-values measured in this experiment are significantly lower than T_i-values in the hot zone, according to the PROGNOZ-data).

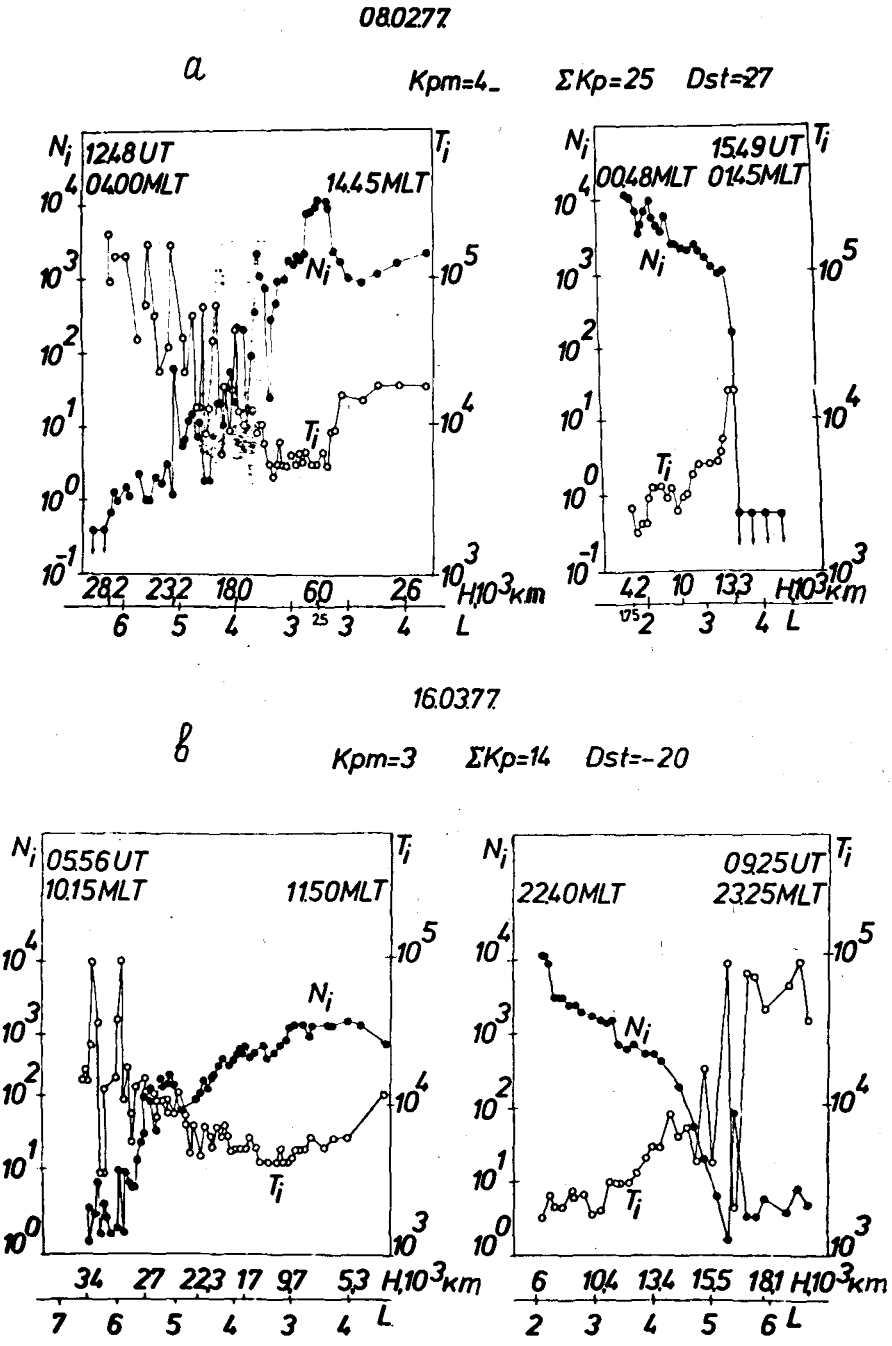

Fig. 5. n_i (L, H) and T_i (L, H) distributions derived from the Prognoz-5 RPA data. The UT time values are given for the beginning and end of each satellite passage through the plasmasphere, MLT times – for the beginning and end of each curve; K_{pm} is the maximum K_p-index of the previous day; ΣK_p is the sum of K_p-indices of the previous day; the Dst index corresponds to the measurement time.

At the same time, as has been mentioned and can be seen from Figure 1, Horowitz and Chappell (1979) estimated T_i in the outer zone as ≤ 8 eV (close to Bezrukikh and Gringauz' (1976) estimation) but they considered the T_i values as unknown in the inner zone. This fact emphasizes the importance and the urgency of T_i measurements along the whole plasmasphere, including tubes with small L-coordinates.

The technique used for determining temperature of plasmaspheric ions T_i (Bezrukikh and Gringauz, 1976), was based on the measurement of the anisotropy of the cold ion fluxes in a coordinate system connected with the satellite, i.e., on the assumption of a Maxwellian ion velocity distribution and an anisotropy completely determined by the satellite motion. In other words, it was suggested that (a) the fluxes of the isotropic energetic particles are negligible when compared with the measured flows of the cold plasma; (b) the plasma drift velocity is also negligible when compared with the satellite velocity. Suggestion (a) was criticized by Krinberg *et al.* (1981) and suggestion (b) by Vlasov and Tashkinova (1981); both papers expressed doubts about the existence of the 'hot zone' with ion temperatures up to 10 eV.

New distributions of $n_i(L)$ and $T_i(L)$ were obtained by the retarding potential (RPA) technique on PROGNOZ-5 satellite (Gringauz *et al.*, 1981). Since only the abstract of this paper has been published, it is reasonable to give some details of this experiment. A detailed description of the experiment and of the results obtained will be published elsewhere.

PROGNOZ-5 was launched during the IMS on 24 September, 1976 to an orbit with a 65°-inclination to the equator and an apogee of 196200 km; the perigee grew from initially 500 km to $\sim$ 2000 km on 12 March, 1977 (the apogee changed very little during this time). The satellite axis of symmetry (rotation axis) was oriented to the Sun and the period of revolution around the Earth was $\sim$ 4 days. The paper uses the data from the flat ion RPA (Gringauz *et al.*, 1981) located on the part of the satellite shaded from the Sun, with an aperture perpendicular to the rotation axis. The processing of the retardation-curves (ion probe characteristics) was carried out in such a way that the effect of ions with fluxes energies $E > 25$ eV and electrons with $E < 100$ eV was eliminated. The steepness of slope of the retardation curve in a semilogarithmic scale (in accordance with Langmuir's theory) depended on the T_i-value. The presence of two slopes could be caused either by the presence of the second kind of ions (heavier than protons) or by the presence of two components of the proton plasma with different T_i-values.

The processing of the retardation curves with one linear portion was performed under the assumption of Maxwell distribution of ion velocities; all ions were supposed to be protons, and least squares method was used for matching the parameters of the analytic expression (which included the satellite velocity (known), n_i, T_i and the satellite potential Φ_{sp}) to the theoretical and experimental probe characteristics. The processing of 'broken' retardation curves was more complicated. The defined T_i values depend neither on the simultaneous existence of more energetic particles nor on the drift velocity of the plasma (which does not affect the steepness of retardation curve). Therefore, the assumptions mentioned above (a) and (b) that led to some doubts about the 'hot zone' of the plasmasphere are not used in this experiment.

Figure 5 gives samples of n_i and T_i distributions of the Maxwell component of plasmaspheric ions depending on L and H (H is the satellite altitude over the Earth's surface). Left plots refer to daytime and right plots to nighttime.

The presented graphs demonstrate the 'midday bulge' of the plasmasphere. In the outer plasmasphere ($L > 3$–4), T_i begins to increase for all the cases mentioned: in cases (c) and (d) T_i reaches 10^5 K with $n_i \lesssim 10$ cm^{-3}. The shape of the retardation curves evidences frequent significant violations in the Maxwell distribution and the possible increase of the abundance of other ion components (besides protons). These results match the conclusions made by Bezrukikh and Gringauz (1968) that the outer zone of the plasmasphere is variable and differs from the inner zone by higher ion temperatures.

The number-density of ions in Figure 5 for $T_i \gtrsim 10^5$ is approximately one order of magnitude lower than that in Bezrukikh and Gringauz's paper (1976); in approaching the plasmapause the errors in determining n_i increased substantially.

The PROGNOZ-5 measurements of T_i mentioned above put an end to doubts (Krinberg *et al.*, 1980) associated with the assumption about the decisive influence of the recordings of ring-current particles on the T_i measurements made by Bezrukikh and Gringauz (1976), because the effect of the ring-current ions was excluded in the PROGNOZ-5 experiments while measuring T_i. Ions with high T_i values were observed by many satellites, as we have seen, and the results of Krinberg *et al.* (1980) calculations can only indicate that the theoretical model they used is not adequate.

The agreement between the PROGNOZ (Bezrukikh and Gringauz, 1976) and PROGNOZ-5 (Gringauz *et al.*, 1981) measurements of T_i also removes the arguments of Vlasov and Tashkinova (1981) who believed that the T_i values determined by Bezrukikh and Gringauz (1976) were considerably overrated, due to not taking into account ion drift in the plasmasphere.

Note that many authors (after Horowitz and Chappell, 1979) call ions in the external zone not 'hot' but 'warm' to distinguish them from those in the plasmasheet.

4. On a Heating Source for the 'Hot' (or 'Warm') Zone of the Plasmasphere; Ring Current Interaction with the Plasmasphere

While there is no doubt about the ionospheric origin of the plasma in the plasmasphere, the T_i-values in the outer plasmasphere are significantly higher than those in the F-region of the ionosphere near the foot of the same flux tubes. What is the source of heating the 'hot' (or 'warm') zone of the plasmasphere? If Horowitz *et al.* (1981b) are right (they reported about the results of simultaneous observations of the plasmasphere from the SCATHA satellite and of images of the auroral oval obtained from the DMSP satellite), the plasmapause often coincides with a field line passing through the low-latitude boundary of the auroral oval with an accuracy better than $0.1L$. The possibility to define the real position of a field line at high altitude with such accuracy, and at comparatively high L, causes some doubts, especially during magnetic disturbances. Nevertheless, Horowitz *et al.*'s communication (1981) can be considered as evidence that magnetic flux tubes of the outer plasmasphere (adjacent to the plasmapause) are located in the midlatitude ionospheric trough located inside the polar oval low latitude boundary. T_i in the midlatitude trough is fastly increasing with altitude ($T_i \sim 6000$ K at $H = 2500$ km according to ISIS-1 satellite data, Miller (1974)). The significant increase of T_i with altitude over the ionospheric trough is obvious evidence that the heat source is located above the ionosphere, i.e., in the outer plasmasphere.

Serbu and Maier (1970) suggested that hot ions near the plasmapause are ionospheric ions belonging to a tail of Maxwellian distribution, which are temporarily trapped by the geomagnetic field. However, we have already noted that this mechanism cannot explain the morphology and dynamics of the 'hot' zone, because it should be applicable to the inner plasmasphere too (Gringauz, 1976). For the present, the only suggested candidate of the plasma heating source in the 'warm' zone of the plasmasphere that meets the condition of heating inside this zone is the dissipation of energy of the ring current during its decay at the magnetic storm recovery phase.

Cornwall (1970) suggested a mechanism for heating plasmaspheric electrons by electromagnetic ion-cyclotron waves (occurring during ring-current interaction with the cold plasmaspheric plasma); in the process of Landau damping of these waves, the electrons gain energy. Later, this author noted that if the admixture of heavy ions reaches 20% of protons, ion-cyclotron waves do not appear (Cornwall, 1971).

It follows from Serbu and Maier's (1970) results as well as from the comparison of PROGNOZ T_i data (Bezrukikh and Gringauz, 1976; Gringauz *et al.*, 1981) with T_e data from the GEOS-1 satellite (Décréau *et al.*, 1982), that $T_i > T_e$ in the outer plasmasphere. Hence, we need a mechanism that makes it possible to heat ions more intensively than electrons. A mechanism suggested by Galeev (1975) involves ions heated by induced scattering of ion-cyclotron waves up to values $T_i > T_e$. In this case the measured values of T_i are in agreement with the data measured in the 'warm' zone.

Until recently, the plasmasphere interaction with the ring current has been considered only in the discussion of mechanisms of ring-current decay (e.g., in the review of Lyons (1976)). After the composition of energetic ions (with $E/q \leq 16$ keV/q) was measured, it was found that this interaction can also manifest itself when ions of the ring current are replenished by ions from the plasmasphere (Balsiger, 1981). In the papers by Balsiger *et al.* (1980) and Balsiger (1981), it is mentioned that during the main phase of the storm the inner edge of the ring current lies typically within the plasmasphere. Let us note that this has already been suggested based on plasmasphere measurements by Besrukikh and Gringauz (1976).

In Section 2 we mentioned an unusually high number-density ratio of plasmaspheric ions O^{2+}/O^+ observed in the plasmasphere. Similarly, high O^{2+}/O ratios and/or high He^+/He^{2+} ratios which cannot be observed in the solar wind and in the ionosphere are sometimes detected in mass-spectra of plasmasheet magnetospheric particles in the keV range of E/q (Balsiger *et al.*, 1980; Balsiger, 1981). This was a reason to argue that it is not only the solar wind and the ionosphere that are the sources of high-energy magnetospheric charged particles, but the plasmasphere as well. Figure 6 shows the

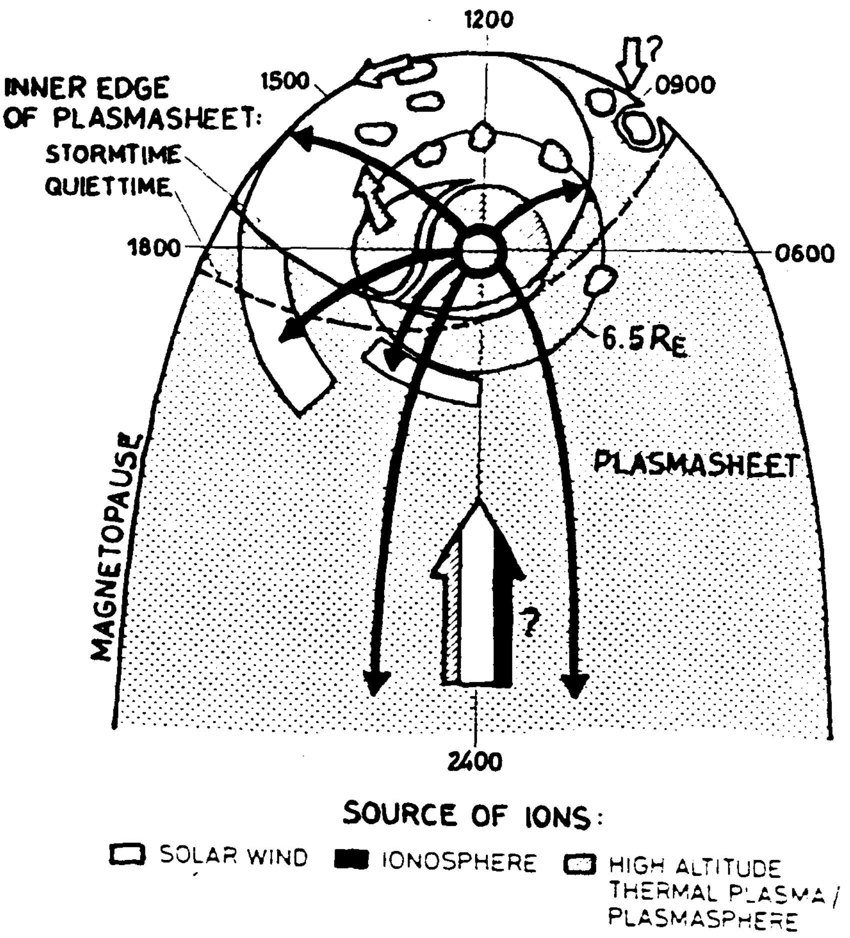

Fig. 6. A sketch of magnetospheric convection, with the plasmasphere taken as a plasma source.

diagram of the magnetospheric convection with all three sources mentioned (Balsiger, 1981).

5. Conclusions

(1) In recent years plasmasphere studies have begun using, along with whistlers and earlier satellite instruments (wide-angle plasma detectors, ion-mass-spectrometers), more sophisticated devices which allow measurements of ion-mass spectra with a higher sensitivity, pitch-angles and energy distributions of ions of each mass. The 'mutual-impedance' probe is an advanced technique successfully used in the studies of the electron component of the plasmasphere.

(2) Investigations conducted in recent years by whistler observations and from GEOS-1 and Prognoz-5 have confirmed the existence of the noon-midnight asymmetry (dayside bulge) of the plasmasphere found with Prognoz satellite measurements.

(3) All satellite packages with an objective to study ions (ATS-6, GEOS-I, ISEE-I, Prognoz-5) observed plasma ion temperatures of $T_i \sim 10$ to 20 eV in the outer plasmasphere. The data agree with the suggestion by Bezrukikh and Gringauz (1976) that (i) a variable 'hot' plasmasphere zone exists at $L \gtrsim 3$ with $T_i \gtrsim 1$ eV; (ii) near the plasmapause T_i increases up to ~ 10 eV; and (iii) the 'hot' zone differs from the 'cold' zone at $L \lesssim 3$ which is stable and has $T_i < 1$ eV. It is more convenient to call the former a 'warm' zone (since the plasma in the plasma sheet is often called 'hot'). Comparison of T_i values and the T_e values near the plasmapause measured with OGO-5 and GEOS-1 satellites (Serbu and Maier 1970; Gringauz, 1976; Décréau *et al.*, 1982) shows that in this region $T_e < T_i$ and that the mechanism of preferential ion heating does exist there.

(4) Three types of ion pitch-angle distributions have been identified in the warm zone of the plasmasphere: (a) A distribution with the maximum along the geomagnetic field **B** (it obviously corresponds to plasma motion along a flux tube);(b) A distribution with the maximum perpendicular to **B** (of 'pancake' type) (it evidently corresponds to the ions trapped by the geomagnetic field); (c) A conical distribution, with the maximum in the 20 to 40° pitch-angle region.

Authors of the pitch-angle measurements argue that the (b)- and (c)-type distributions could form due to ion-cyclotron wave effects on the ions in the outer plasmasphere.

(5) The GEOS-1 and -2, ISEE-1 measurements detected He^{2+} and O^{2+} not observed earlier; an unusually high O^{2+} ion abundance may be attributed to thermal diffusion (for assumptions realistic for $L = 3$: $T_i = 10^3$ K in the ionosphere and $T_i = 10^4$ K in the equatorial plane).

(6) The 'warm' plasmasphere zone could form as a result of cold plasma heating owing to its interaction with the ring current, with a preferential heating of ions. The specific heating mechanism could be related to the decay of ioncyclotron waves.

(7) The high abundance of O_2^+ ions with energies of the order of 1 keV in the plasma sheet (Balsiger, 1981) implies an assumption that ring-current sources include the plasmasphere along with the solar wind and the ionosphere.

The following are some unsolved problems:

(1) Definite identification of electron and ion heating mechanisms in the warm zone (outer plasmasphere).

(2) Clarification of physical processes (depletion and filling of flux tubes; electric fields, interaction between waves and particles) that determine the type of ion pitch-angle distributions observed.

(3) Determination of the relative position of the boundaries of the main ionospheric trough and the plasmapause and dependence on geomagnetic activity and prehistory.

Finally, although the present state of plasmapause-formation theory is beyond the scope of this review, it is worth mentioning that a complete and convincing theory that explains most of the typical features (e.g., including not only the morning/evening plasmapause asymmetry but also the midnight/noon asymmetry as well) has not yet been developed.

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