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THE STRUCTURE OF THE PLASMASPHERE ON THE BASIS OF DIRECT MEASUREMENTS

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Abstract. The plasmasphere is the outermost region of the ionosphere which extends up to several earth radii. It is filled with a collisionless cold plasma in which the geomagnetic field is frozen. The data obtained from the first measurements in this region (up to 1963) are given as a background. The information from experiments carried out after 1963 by means of charged particle traps, ion mass spectrometers, and Langmuir probes installed on satellites of the Electron, IMP, and OGO series is reviewed. It comprises the space distribution of ion and electron densities, their dependence on geomagnetic activity and local time, ion composition of the plasmasphere, and charged-particle temperatures. The possibility of detection of the plasmapause by the observation of more energetic charged particles is mentioned, and the results of in situ measurements are briefly compared with whistler results.

The importance of plasmasphere study for the geophysics is outlined.

1. Introduction

1.1. DEFINITIONS

Generally accepted terminology relating to all parts of the ionosphere, the envelope of ionized gas that surrounds the earth, does not as yet exist. In this review, only the outermost region of the ionosphere is considered; the region filled with collisionless plasma (consisting basically of ionized hydrogen particles – protons and electrons – having thermal energies) with a frozen-in magnetic field. The upper boundary of this region is, on the average, situated at a geocentric distance R of about 4.5 times R_E (the earth's radius). The degree of ionization in this region is very high – at $R \sim 2.5\ R_E$ (height $Z \sim 10000$ km), the density of neutral hydrogen $n_0 = 10^3\ \text{cm}^{-3}$ (Kurt, 1967), while for this case the average ion density n_i is also $\sim 10^3\ \text{cm}^{-3}$ (Bezrukikh and Gringauz, 1965). The term plasmasphere (introduced by Carpenter, 1966) shall be used to denote this specific region in this review. It has often been called the 'protonosphere' (Geisler and Bowhill, 1965; Gliddon, 1966; Nagy *et al.*, 1968), but we shall not use this term, since, for example, the region close to the maximum of the F layer is not called the 'oxygensphere'.

The upper boundary of the plasmasphere will be called the *plasmapause* (Carpenter, 1966).

Observational results of the plasmasphere published prior to 1967, and some of the problems relating to its formation and existence, were briefly summarized at the Washington symposium of the physics of the magnetosphere (Gringauz, 1969; Axford, 1969; Helliwell, 1969).

In the present review a part of the data reported in Washington is used, and the new results, which become recently available, are included.

1.2. METHODS OF INVESTIGATING THE PLASMASPHERE

Direct observational studies of the plasmasphere are made with the help of such

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instruments as charged-particle traps, ion mass-spectrometers, and Langmuir probes, carried aboard rockets and satellites (Gringauz *et al.*, 1960a; Gringauz *et al.*, 1960b; Gringauz, 1961; Bezrukikh and Gringauz, 1965; Taylor *et al.*, 1965; Serbu and Maier, 1966; Binsack, 1967; Vasyliunas, 1968a; Brinton *et al.*, 1968; Taylor *et al.*, 1968a, 1969; Bezrukikh, 1968; Chappell *et al.*, 1969; Chappell *et al.*, 1970; Harris *et al.*, 1970; Freeman *et al.*, 1970).

All methods of obtaining information on the plasmasphere which use electromagnetic radiation of natural or man-made origin, be it radiation with very low frequency, for example, whistlers, or with very high frequency (incoherent backscatter radar technique), and independent of whether the observations are carried out on earth or on a satellite, are the subject of a review article, elsewhere in this volume (Helliwell, 1972).

Studies of whistlers from ground-based devices (Carpenter, 1963; Carpenter, 1966; and many other papers) made great contributions to the formulation of contemporary ideas on the physics and dynamics of the plasmasphere. The special value of this method lies in the fact that it is possible to make continuous measurements, thus obtaining, comparatively cheaply, vast quantities of initial observational results. However the possibilities of this method are limited; it gives information on the electron densities only in the geomagnetic equatorial plane, and does not give any information on the electron energy.

Information on the details of electron-density distributions outside of the equatorial plane may be obtained from low-frequency electromagnetic radiation data, obtained from satellites (Carpenter *et al.*, 1969).

Satellite studies of so-called ion whistlers give more information about the surrounding plasma (including ion temperature), but this method can be used only at comparatively low heights (Gurnett and Brice, 1966).

Diverse and valuable information on the variation of the ionospheric plasma parameters with height above the point of observation may be obtained by the method of incoherent backscattering of radio waves. The present state of technology, however, does not allow us to investigate the region of heights corresponding to every layer of the plasmasphere, including its most interesting region, the plasmapause.

The limitations, which are inherent in indirect methods of study of the plasmasphere, are mentioned here only so that we may correctly evaluate the place and value of the direct methods of observation, listed above.

With the help of the direct methods, it is possible to define all parameters of the plasmasphere (ion and electron densities, ion mass composition, energy distribution, etc.) at any latitude, and to obtain data for the construction of a full, three-dimensional model of the plasmasphere.

Such measurements, however, in which it is necessary to register and analyze charged particles with the smallest energies found in space, and with rather low densities, entail significant experimental problems. Despite the significant efforts made in pre-flight calibration of the instrument (for example, Brinton *et al.*, 1968), it has not been possible to fully eliminate the influence of all factors that distort the results of direct measurements. One of these, particularly, is the change in electrical potential of the spacecraft during the flight: this influences the spatial and energy distribution of the charged particles in the neighbourhood of the spacecraft in a highly rarefied medium. Photoemission of electrons from the surface of the spacecraft makes the measurements of the electron component of the plasma especially difficult.

In some cases, authors of the experiments quote a low accuracy for the measurements (for example, to a factor of 5 – Taylor *et al.*, 1965; Gringauz, 1969); in other cases, authors prefer not to give the magnitude of the charged-particle density, and restrict themselves to defining the position of the plasmapause (Binsack, 1967).

Although many of the results obtained appear to be indisputable, even when the authors of the direct measurements do not consider it necessary to emphasize the fact that their measurements are rather rough, some caution is necessary when using data from direct measurements.

1.3. FIRST OBSERVATIONS ON THE PLASMASPHERE

The first information on the existence of the cold plasma envelope around the earth, with boundaries at geocentric distances $R \sim 4\ R_E$, was published in 1960, in the description of the experiments carried out in 1959 on the first Soviet lunar rockets. The simultaneous use of four traps with different potentials retarding positive ions showed that the plasma temperature does not exceed few tens of thousands of degrees (Gringauz *et al.*, 1960a, b).

In April, 1961, at the second COSPAR symposium a report on the structure of the earth's ionized gas envelope was presented. In this report the problem of the upper boundary of the ionosphere was discussed: "Experiments on board the artificial satellites and space probes compel now to seek paths for creating a new theory which would adequately explain the facts we have acquired of late. Among these facts is the significant increase of negative gradients of ion concentration revealed in the range of altitudes 15000–20000 km, near the boundary of the earth's gas envelope" (Gringauz, 1961).

Actually two different theories which could qualitatively explain the existence of the break in the plasma density distribution with height, that occurs at an altitude of a few earth radii, (in current terminology – the plasmapause) were proposed in that same year, 1961.

Almost simultaneously with the publication of the experimental results obtained from the plasma-detectors on the lunar rockets, but independent from them, models of the magnetosphere were proposed in which there were convective motions of plasma in the external regions, such that an electric field would be produced in the equatorial plane directed across the magnetosphere (Dungey, 1961; Axford and Hines, 1961). In this model, a forbidden zone is formed close to the geomagnetic dipole, into which the plasma that takes part in the convection can not enter. The boundaries of this zone are formed by the 62° line of latitude which corresponds, in the equatorial plane, to a geocentric distance of $\sim 4.5\ R_E$ (Axford and Hines, 1961). In this manner, the upper atmosphere, which is ionized by solar radiation, is found in the forbidden zone.

Of course, the laws relating the change in plasma density with geocentric height inside the forbidden zone, and outside of it, should be different.

In 1962, measurements of cold plasma, at geocentric distances up to $\sim 4\ R_E$ on high geomagnetically invariant latitudes ($\Lambda = 72°$), were made with instruments on board the Mars 1 rocket (Gringauz *et al.*, 1964). We shall return later to these observations – as far as is known, they have not been repeated for these particular heights and geomagnetic latitudes.

In 1963 Carpenter presented results showing electron-density distributions as a function of height, in the plane of the geomagnetic equator, which were obtained from analyses of ground-based observations of whistlers. In the $n_e(R)$ profiles, he found, at a geocentric distance of $\sim 4\ R_E$, a region where n_e decreases more rapidly and called this the 'knee' (Carpenter, 1963). The $n_e(R)$ profile from the whistler data is shown in Figure 1, which is taken from Carpenter's first report. The circles in this figure show the data obtained from detectors on Luna 2. The author remarked that the two sets of data were in agreement.

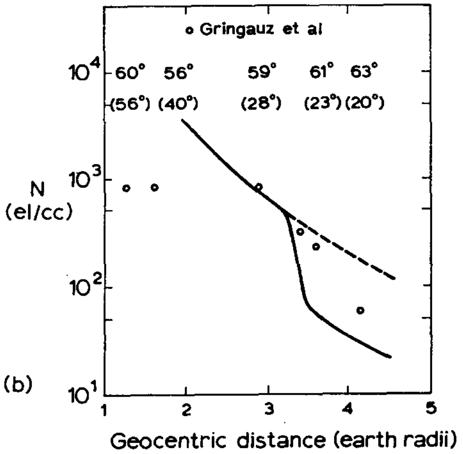

Fig. 1. Charged particles density versus geocentric distance from data obtained by means of the ion traps on Luna 2 and from whistler data (Carpenter, 1963).

This report formed an important step in the study of the earth's plasma envelope, and it proved to be the beginning of a series of continuous studies by Carpenter himself, and by others. The results of these studies explained for the first time a number of peculiarities of the global structure and dynamics of the plasmasphere (continuous measurements of the height of the plasmapause in the equatorial zone, reactions of the plasmasphere to changes in geomagnetic activity, etc.).

The studies of the plasmasphere from whistler data are described in sufficient detail in Helliwell's review article (Helliwell, 1972), and so, here they will be mentioned only in so far as necessary to make comparisons to the data obtained by direct measurement.

In the present review, the data obtained from the various spacecraft are used as indicated in Table I.

TABLE I

Spacecraft data used

Spacecraft	Date of launching	Perigee (km)	Apogee (km)	Inclination to equator	Devices[a]
Luna 1	2. 1.59				Charged-particle traps
Luna 2	12. 9.59				Charged-particle traps
Mars 1	1.11.62				Charged-particle traps
Electron 2	30. 1.64	460	68200	61°	Charged-particle trap
Electron 4	11. 7.64	460	66235	61°	Charged-particle trap
OGO 1	5. 9.64	280	150000	31°	Charged-particle trap of modulation type (Faraday cup), ion mass-spectrometer
IMP 2	4.10.64	197	93910	33°	Charged-particle trap of modulation type (Faraday cup), charged-particle trap-retarding potential analyzer
OGO 2	14.10.64	415	1525	88°	Ion mass-spectrometer
OGO 3	7. 6.66	295	122000	31°	Ion mass-spectrometer, charged-particle trap of modulation type, cylindrical electrostatic analyzer
OGO 5	4. 3.68	282	145500	31°	Ion mass-spectrometer, Langmuir probe

[a] only devices data of which are used in this review are mentioned.

2. The Plasmapause at Low Geomagnetic Latitudes and its Variations

2.1. GENERAL MORPHOLOGY

The year 1964 proved to be very fruitful for further plasmaspheric studies, for, within that year, 4 satellites were launched into eccentric earth orbits with high apogees, carrying on board instruments to measure very low-energy charged particles. These satellites were the USSR Electron 2 and Electron 4, and the USA IMP 2 and OGO 1 (see Table I).

Figure 2 shows the first results of the ion density distribution measurements made with charged-particle traps on board Electron 2, in 1964, and this figure clearly shows the region of sharply decreasing ion density – the plasmapause (Bezrukikh and Gringauz, 1965). In the results obtained from OGO 1, using a radio-frequency mass-spectrometer, the plasmasphere was clearly observed, almost simultaneously in both the proton and helium components (Taylor *et al.*, 1965). Because of the fact that the inclination of the OGO 1 orbit to the equator and, as far as is known, the inclination to the equator of other satellites having highly eccentric orbit and having instruments (for studying the plasmasphere) is $\sim 31°$, all data obtained from this satellite refer to geomagnetic latitudes of $\leqslant 45°$.

Using the data obtained by direct measurements made on satellites whose orbits are inclined to the equator, it is possible to determine the position of the plasmapause in a meridional plane. Generalizing the ground-based observations of whistlers, and

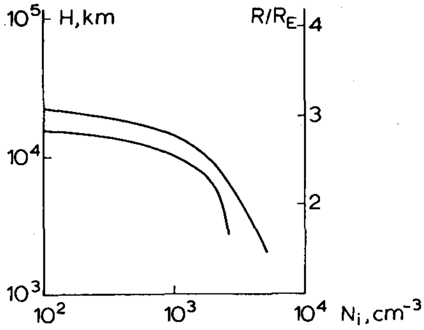

Fig. 2. Distribution of ion density with height obtained by means of the charged particle trap on board Electron 2 satellite. The upper curve corresponds to 2.2.1964, the lower to 2.13.1964 (Bezrukikh and Gringauz, 1965).

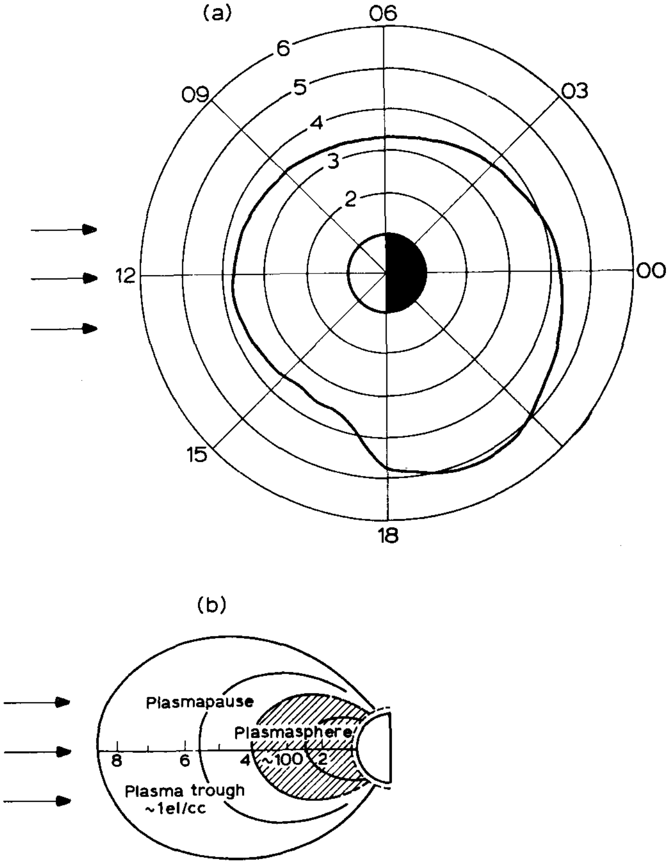

Fig. 3. Model of the plasmapause for moderate geomagnetic activity (a) equatorial cross-sections; (b) meridional cross-section (LT ~ 14 h) (Carpenter, 1966).

ion measurements obtained by Taylor *et al.* from the OGO 1 satellite, Carpenter (1966) published a model of the plasmasphere, shown in Figures 3a and 3b.

Figure 3a shows the dependence of the geocentric distance of the plasmapause in the equatorial plane on local time, corresponding to an average value of geomagnetic activity. A notable feature of this diagram is its asymmetry, caused by the presence of the bulge in the evening region.

When geomagnetic activity increases, the plasmasphere is compressed, and its asymmetry increases; and when it decreases, the plasmasphere moves away from the earth in the equatorial plane to a distance of $R=6\ R_E$, and the asymmetry decreases (Carpenter, 1966).

Figure 3b shows a meridional cross-section of the daytime side of the plasmasphere ($\sim$14h LT). The shaded region is bounded by the magnetic shell $L=4$ and has an electron density of $n_e \sim 100\ \mathrm{cm}^{-3}$ which, close to the plasmapause, and $\sim 1\ \mathrm{cm}^{-3}$ outside. For geomagnetic latitudes $>45°$, the cross-section of the plasmasphere is indicated by a dashed line, because the author of the model lacked observational data for this region.

On the IMP 2 satellite, observations of the cold plasma were made with charged-particle traps using retarding potentials (Serbu and Maier, 1966), and with traps of the modulation type (Binsack, 1967). The authors of the former experiment, after reducing the data, did not find the region of sharply decreasing plasma density – the plasmapause; whereas in the latter experiment, it was observed. As far as we know, the results of investigation of the causes of why the data of the former experiment contradict the numerous results of other authors, has not yet been published.

To evaluate the reliability of the measurements of n_i, data on ion and electron densities at geocentric distances of $\sim 2\ R_E$ were obtained from five independent experiments and compared (whistler data and data obtained from the Electron 2 and OGO 1 satellites were included). In all cases, the density was found to lie between the limits $2\times10^3\ \mathrm{cm}^{-3}$ and $4\times10^3\ \mathrm{cm}^{-3}$ (the data from Electron 2 and OGO 1 were taken at a time near the minimum of the solar activity cycle) (Brinton *et al.*, 1968).

Figure 4 shows the distributions of n_i as functions of the McIlwain L parameter obtained using a mass-spectrometer at the time of maximum of solar activity, in March 1968, during the first 4 revolutions of the satellite OGO 5 around the Earth (Harris *et al.*, 1970). In all cases of $L=2$, n_i has the value of a few thousands per cm^3, and reaches, in one case (profile 7) a value of $\sim 10^4\ \mathrm{cm}^{-3}$.

In six out of the eight profiles, the plasmapause is clearly visible (the exceptions being profiles 1 and 4). The somewhat unusual $n_i(L)$ profile number 6 is interesting for it has two regions of sharply decreasing n_i (for $L=4$ and for $L=5.8$). In some of the $n_i(L)$ profiles, oscillations were observed. The authors of this paper referred to a private communication from P. Coleman, noting that simultaneous measurements made on the same satellite showed that there were oscillations in the magnetic field. Therefore the authors considered these results as evidence of some spatial fluctuations (in L). It should be noted here that, with data from only one spacecraft, it is not possible to determine whether the fluctuations are spatial or temporal.

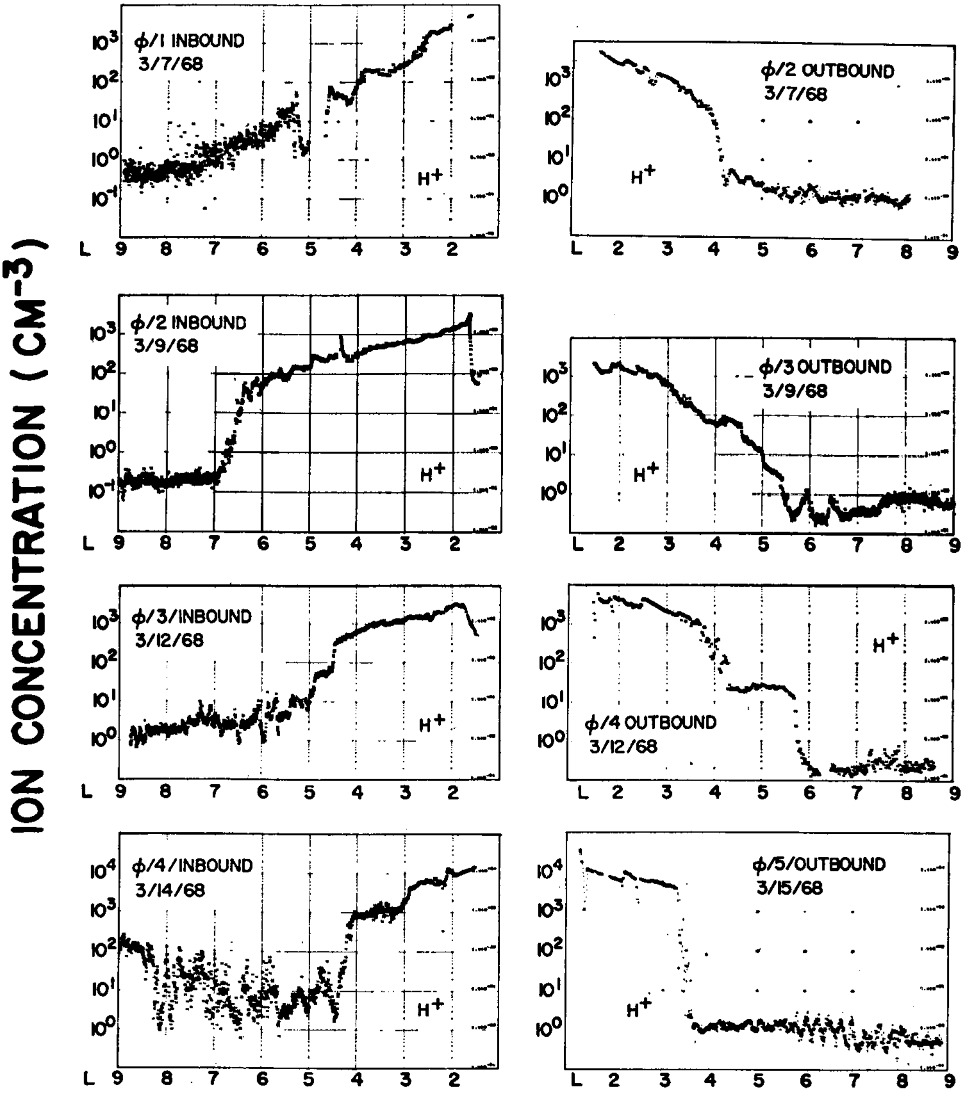

Fig. 4. H$^+$ ion density distribution [$n_i(L)$ profiles] from ion mass-spectrometer data obtained on board the OGO 5 satellite (Harris *et al.*, 1970).

From the $n_i(L)$ profiles of Figure 4, it is evident that the position of the plasmapause changes within wide limits from $L\sim3.5$ (profile 8) to $L=6.5$ (profile 3).

2.2. DEPENDENCE OF PLASMAPAUSE POSITION ON GEOMAGNETIC ACTIVITY

Figure 5 shows the dependence of the L coordinate of the plasmapause on the maximum K$_p$ index of each day, preceding measurements obtained in 1964 from the Electron 2 and Electron 4 satellites (Bezrukikh, 1968, Figure 5a), in 1966 from OGO 3

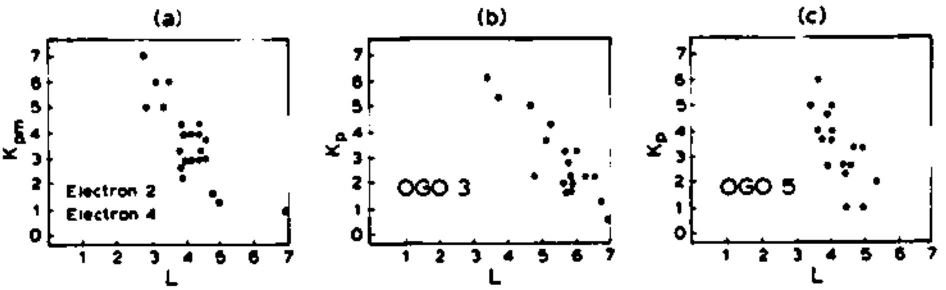

Fig. 5. The relation between L coordinate of the plasmapause (determined from ion density measurements) and K_p index averaged over the preceding 24 h: (a) 1964 – from Electron 2 and Electron 4 data (Bezrukikh, 1968); (b) 1966 – from OGO 3 data (Taylor *et al.*, 1968a), (c) 1968 – from OGO 5 data (Chappell *et al.*, 1970).

(Taylor *et al.*, 1968a, Figure 5b), and in 1968 from OGO 5 (Chappell *et al.*, 1970, Figure 5c).

From the results of observations of the average (not taking into account the local time) position of the plasmapause obtained from the IMP 2 satellite (1964), the following empirical formula for determining the position L, was proposed:

$$L = 6 - 0.6\ K_p \tag{1}$$

where the K_p index to be used corresponds to the time of measurement (Binsack, 1967).

Other authors prefer to use, for comparison, the maximum K_p index for the day preceding the measurement, obviously because of the inertia of the plasmasphere due to the low velocities with which the cold plasma in the magnetosphere moves. Together with this fact, one of the reasons for using the maximum K_p from the preceding day in the drawing of Figure 5, is a historical one – the desire of authors to compare satellite data with the analogous data obtained at first from whistler studies (Carpenter, 1966).

The question of the rate of reaction of the plasmasphere to changes in magnetic activity at various local times was discussed in a paper by Chappell *et al.*, 1970, where they note that the time delay between changes in the geomagnetic activity level and in the plasmasphere position, of 2–6 h agree well in the region of 02 h local time, but for the region of 10 h LT, the agreement of temporary changes of 6, 12, or 24 h do not lead to significantly different results. Around 10 h LT, the drop in density close to the plasmapause, that accompanies an increase in geomagnetic activity, become far sharper. The authors' remark on the advisability of looking for a new index that would characterize the convection of the magnetospheric plasma, and that would be more suitable than the K_p index for comparisons of the type shown in Figure 5.

On the OGO 5 satellite, as well as the ion mass-spectrometer, there was a spherical Langmuir probe, with 6 cm diameter, with which measurements of the electron component of the plasma were made (Freeman *et al.*, 1970). During the flight, the probe was in the shadow of the solar cell panels, for part of the time, and so its measurements were not influenced by photoemission from the surface of the probe (although it is possible that photoelectrons from the illuminated part of the spacecraft could fall into it). The experiment was designed to measure electron densities $\geqslant 10^{-3}$ cm^{-3} (for this magnitude of n_e the Debye radius becomes comparable to the spacecraft dimensions, that is 2.5 m). When the spacecraft is illuminated by the sun, and is in the plasmasphere the photoemission from the spacecraft is considered to be equal to the photoemissive current in the interplanetary medium, and thus is subtracted from the measurements made in the plasmasphere.

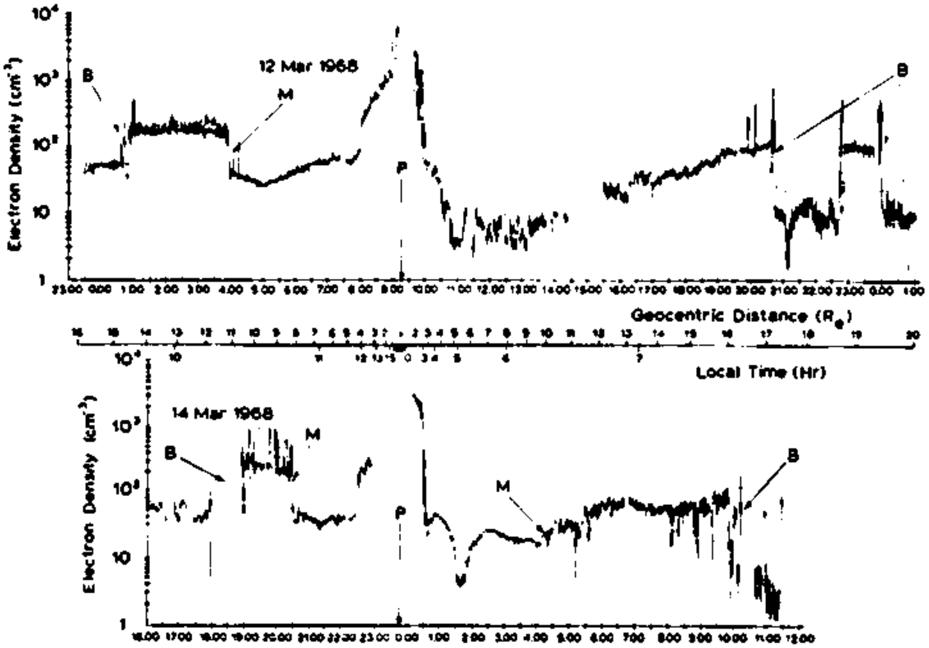

Fig. 6. Samples of $n_e(R)$ profiles obtained by means of a spherical Langmuir probe on board OGO 5 satellite 12 and 14 March, 1968. The arrows marked by the letters B and M indicate the positions of the shock-wave front and the magnetopause respectively; the letter P marks the position of perigee (Freeman *et al.*, 1970).

Figure 6 shows sample $n_e(R)$ profiles, drawn by a computer, with no additional reducing. The arrows marked with the letters B and M indicate the positions that correspond to the shock-wave front, and the magnetopause, respectively, and the letter P marks the position of perigee. These drawings clearly show that the use of Langmuir probes succeeded for the first time in directly detecting the plasmapause in the electron component of the plasmasphere. The data presented in Figure 6 obtained simultaneously with $n_i(L)$ profiles nos. 5, 6, 7, and 8 in Figure 4. If one takes into account the fact that for OGO 5 the geocentric distance in earth radii is only a little smaller than the L coordinate, then the agreement between the position of the plasmapause, as determined from the n_e data from the Langmuir probe, and from the n_i data from the ion mass-spectrometer, may be considered satisfactory.

2.3. THE DIURNAL BULGE

An important characteristic of the plasmapause in the equatorial cross-section of the plasmasphere is the bulge in the evening sector, that was discovered in whistler studies and was shown in Figure 3a.

The bulge was also observed in the results obtained from traps on board the Electron 2 and Electron 4 satellites, in which the magnitudes of the L coordinates of the plasmapause were systematically higher in the evening region than in the morning region (Bezrukikh, 1968). It was also observed on the OGO 1 and OGO 3 satellites (Brinton *et al.*, 1968).

The OGO 5 satellite passed through the evening sector more than 30 times encountering various levels of geomagnetic activity. Using the ion mass-spectrometer on board, a number of detailed $n_i(L)$ profiles, close to the boundaries of the bulge, were obtained, from which the authors of the measurements drew a number of conclusions about the structure and dynamics of this region of the plasmasphere (Chappell *et al.*, 1969).

First of all, the authors noted that, for different levels of geomagnetic activity, the bulge, on the average, is symmetrical about the meridian LT = 18 h. This result agrees with Figure 7, which shows the location of the plasmapause, encountered by the satellite in the vicinity of the 18 h meridian, for the various K_p indexes. The authors of the ion mass-spectrometer experiment consider that the results of their measurements agree well with a picture of the phenomena in the region of the bulge, that may briefly be described as follows: as the magnetic activity decreases, the electric

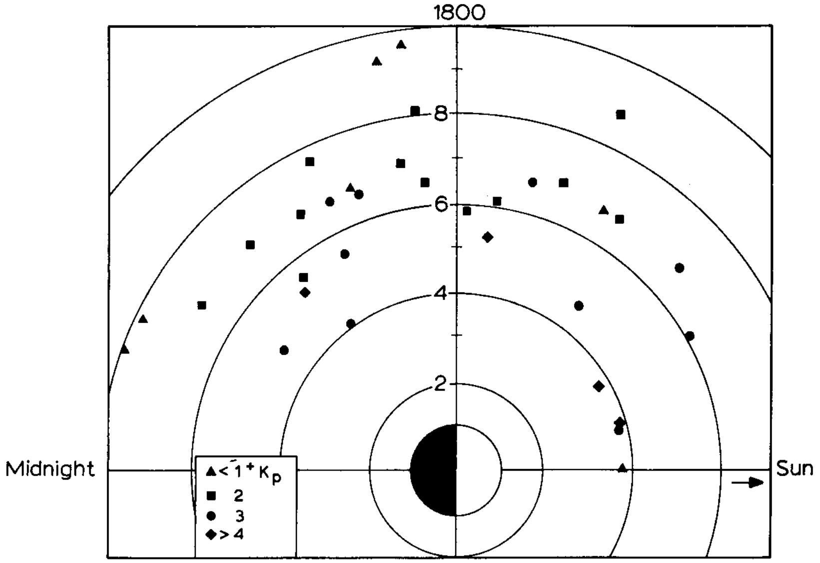

Fig. 7. Locations of the plasmapause in the vicinity of the bulge in the dusk sector of the magnetosphere for the various K_p indexes from the ion mass-spectrometer data taken during 34 passes of the OGO 5 satellite (Chappell *et al.*, 1969).

field across the equatorial section of the magnetosphere (in the direction morning to evening) decreases, the forbidden zone increases, and the bulge becomes filled with plasma from the lower region of the ionosphere.

When the magnetic activity increases, the convection electric field increases and the forbidden zone decreases (the plasmapause moves closer to the earth); in this case, part of the plasma from the bulge can detach from the plasmasphere and take part in the convection, moving towards the day-region of the magnetosphere. Figure 8 shows the $n_i(L)$ profile, corresponding to the passage of OGO 5 through the bulge on October 1, 1968 at 13 h–16 h LT. The plasma detected in the intervals $5.5 < L < 7.7$, is interpreted as separated from the plasmasphere. Before these measurements were taken, the magnetic activity had been low for about one day and then, within ~15 h, it became high. In such a period of time, the total amount of plasma in the plasmasphere decreases.

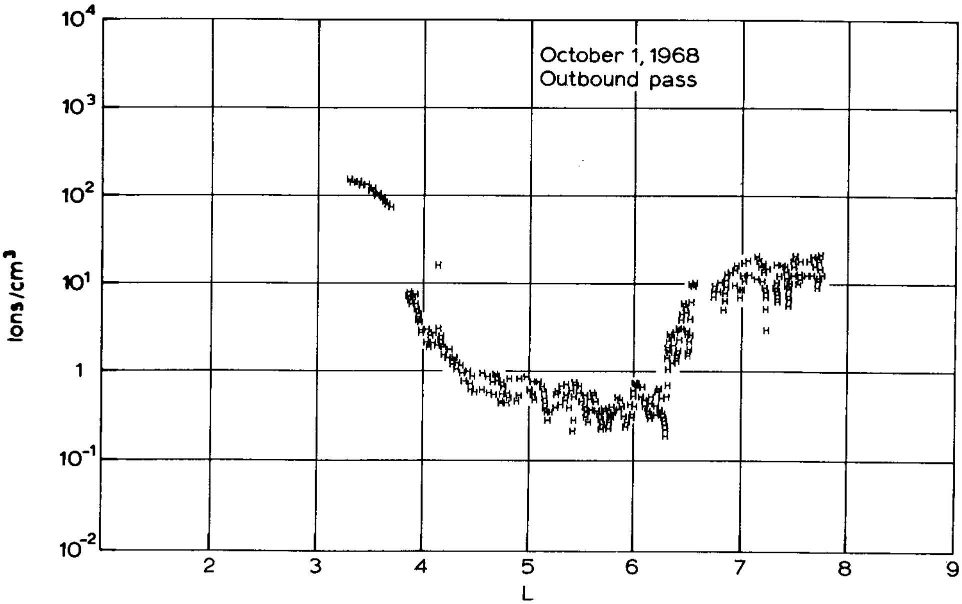

Fig. 8. $n_i(L)$ profile obtained by means of the ion mass-spectrometer on board OGO 5 satellite during its passage through the bulge 10.1.1968 (Chappell *et al.*, 1969). After passing through the plasmapause the satellite registered a plasma cloud separated from the bulge.

This process is illustrated in Figure 9. This figure shows the separation of a cloud of plasma from the bulge, which, on entry into the convecting magnetospheric plasma, moves toward the day region of the magnetopause, then along the magnetopause to the tail of the magnetosphere, where it enters into open field lines and goes off into interplanetary space.

The results of the $n_i(L)$ profile measurements, made with the OGO 5 mass-spectrometer, do not, as the authors remarked, support the suggestion made by

Nishida that the bulge may be considered as 'new' plasma having a non-ionospheric origin), which may exhibit an eddy-type flow (Nishida, 1966).

The conclusion drawn by Chappell *et al.* on the origin, the structure and the mechanism for growth and diminution of the bulge, and their interpretation of experimental data of the type shown in Figure 8, are very interesting and important, although it is possibly still too early to consider them final. Specifically, some concern is caused by the contradiction between two sets of data relating the characteristics of the bulge and magnetic activity. One set, discussed above, was that obtained on OGO 5 which showed that the average symmetry of the bulge around the 18 h meridian was independent of magnetic activity. The second, (reproduced in the preprint of Chappell *et al.*, 1969) was a diagram showing changes of the bulge during changes in magnetic activity that was made by Carpenter from whistler data (Figure 10), in which an asymmetry of the bulge around LT = 18 h is obvious.

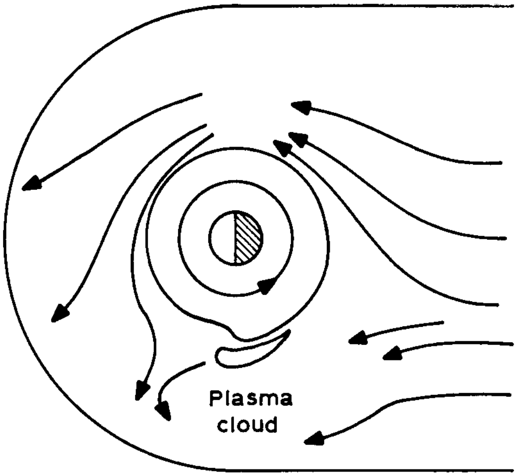

Fig. 9. A possible scheme of motion of plasma cloud detached from the bulge in the equatorial plane of the magnetosphere.

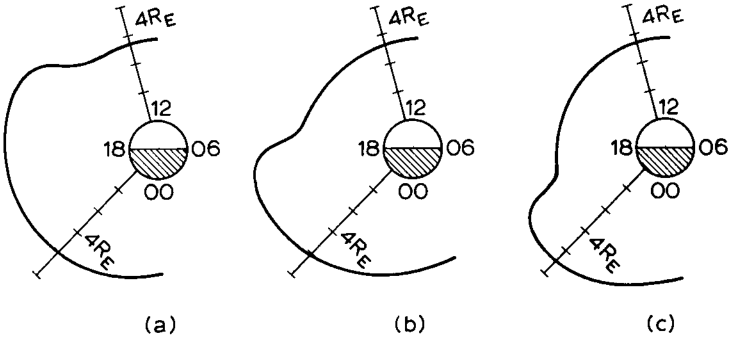

Fig. 10. Form of the bulge (after Carpenter) corresponding to different levels of geomagnetic activity (a) high, (b) moderate, (c) low (Chappell *et al.*, 1969).

One must keep in mind the fact that the OGO 5 satellite crossed the bulge once every 2.5 d, whereas the whistler studies measure the position of the plasmapause almost continuously. Therefore, to resolve this contradiction, a far better statistical sample of satellite data is required, than that used, so far, in the paper by Chappell *et al.* (1969).

2.4. CHEMICAL COMPOSITION OF THE PLASMASPHERE

According to the data obtained from the radio-frequency mass-spectrometer carried on board OGO 1, the density of He^+ ions in the plasmasphere is 1% of the H^+ ion density. The plasmapause is found to be at practically the same heights for both components (Taylor *et al.*, 1965).

Figure 11a shows the $n_i(L)$ profiles obtained from the OGO 3 satellite (Taylor *et al.*, 1968a). One can see from this figure that the results obtained from OGO 3 are in complete agreement with data from OGO 1.

Figure 11b shows the $n_i(L)$ profiles obtained with the magnetically deflecting ion mass-spectrometer on OGO 5 (Harris *et al.*, 1970). Besides the He^+ and H^+ ion distributions, the $n_i(L)$ profile for O^+ ions is also shown. These OGO 5 measurements confirmed the fact that the He^+ ion density is $\sim 1\%$ of the proton density, and showed that the O^+ ion density is $\sim 0.3\%$ of the proton density.

3. Polar Ionosphere and Plasmasphere

According to the idealized model of the meridional cross-section of the plasmasphere, shown in Figure 3b (Carpenter, 1966), beyond the boundaries of the geomagnetic shell that passes through the plasmapause in the equatorial plane, density of cold plasma is very small at all latitudes at sufficiently large heights (>1000 km). In the construction of this model as mentioned above, direct measurements were used (from the ion mass-spectrometer on the OGO 1 satellite). Further data supporting this model were obtained from a number of other experiments. On the Alouette 1 and Alouette 2 satellites, which had orbits with low heights (<3000 km), the plasmapause was detected by the sudden disappearance or diminution of whistlers propagated from the other hemisphere (Carpenter *et al.*, 1968). For values of $L \sim 4$, the plasmapause was found simultaneously by ion mass-spectrometers and wide-band receivers on the OGO 1 and OGO 3 satellites, and also by whistler reception at Antarctic stations (Carpenter *et al.*, 1969). However, although measurements made on the Electron 2 and Electron 4 satellites with charged-particle traps in the vicinity of the equatorial plane were in good agreement with all details of the whistler observational results, the agreement was significantly worse for the $n_i(L)$ profiles, obtained at higher latitudes (Bezrukikh, 1968), on which the plasmapause was absent in a number of cases. Figure 12 shows these $n_i(L)$ profiles obtained from Electron 4 for various levels of magnetic activity. In comparison with the $n_i(L)$ profiles from the OGO satellites, these show a comparatively high value of L for $R \sim (2\text{–}4) R_E$. The decrease in n_i with growth of R or L is monotonic and the magnitude of n_i is rather large far

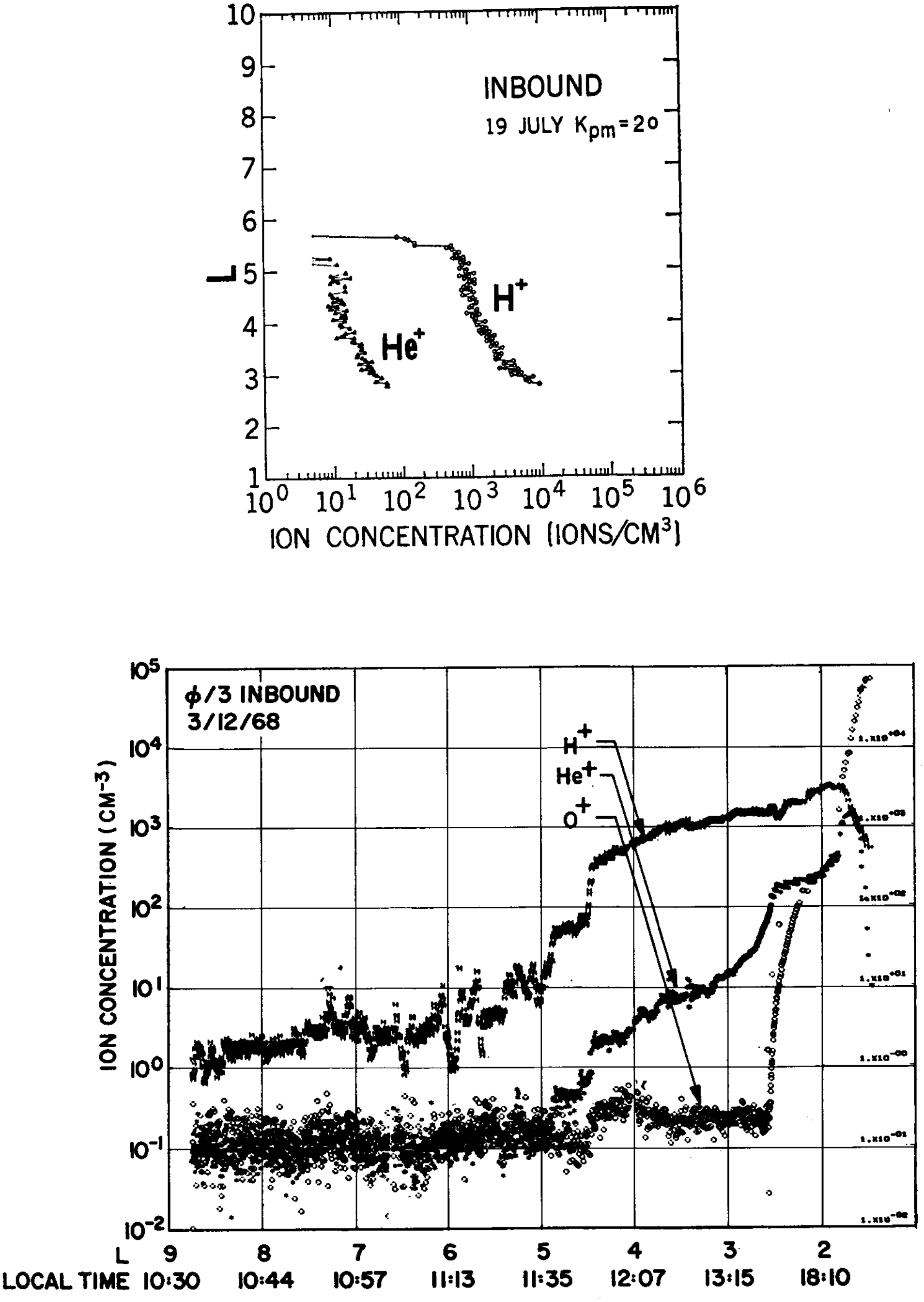

Fig. 11. n_i (*L*) profiles: (a) for H^+ and He^+ ions from data obtained on board OGO 3 satellite (Taylor *et al.* 1968a); (b) for H^+, He^+ and O^+ ions from data obtained on board OGO 5 satellite. (Harris *et al.*, 1970).

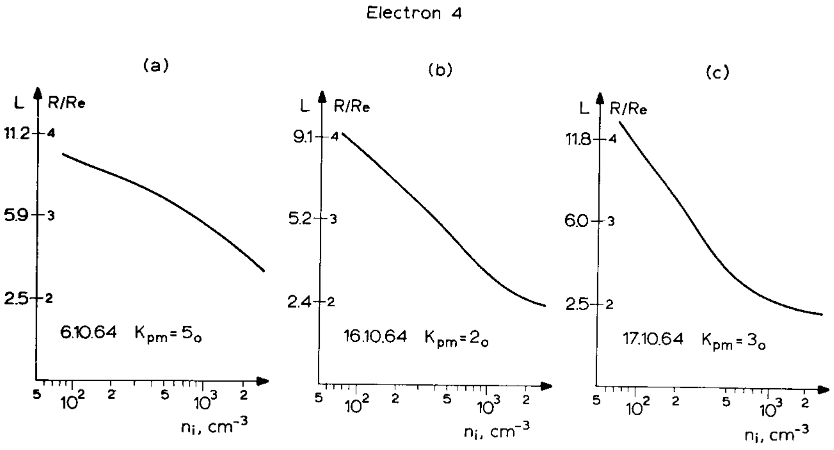

Fig. 12. $n_i(L)$ profiles obtained on board Electron 4 satellite (Bezrukikh, 1968).

beyond the geomagnetic shell, when the plasmapause position should have been given by, for example, Equation (1) above.

A few remarks will now be made on some of the characteristics of the polar ionosphere and the polar wind (although the latter is discussed elsewhere in this volume (Mange, 1972). From a number of satellites with polar orbits at heights of up to 3000 km, and using probes, traps, and ion mass-spectrometers as well as radio methods, it was discovered that, in the upper part of the F layer of the ionosphere, at geomagnetic latitudes of $\Lambda > 60°$, the density of charged particles sharply decreases, in comparison to the density at the same heights at low and middle latitudes, and that the ion composition changes, there being a sharp decrease in the concentrations of the light ions H^+ and He^+ (Bowen *et al.*, 1964; Brace and Reddy, 1965; Taylor *et al.*, 1968b, Taylor *et al.*, 1969; Barrington *et al.*, 1966; Thomas *et al.*, 1966; Hagg, 1967). A number of authors (Bauer, 1966; Dessler and Michel, 1966) explained this phenomenon by the escape of light ions from the polar regions along open field lines; the most complete and well-grounded form of this idea is found in the papers on the polar wind by Axford (1968) and by Banks and Holzer (1968, 1969). The plasmapause (particularly during high magnetic activity) is situated at lower latitudes than the boundaries of the stable zone of trapped radiation (i.e. $L \sim 8$–9, see Vernov *et al.*, 1969) within which the magnetic lines of force are obviously closed. The formation of the plasmapause may be connected with the polar wind (Axford, 1969) by a hypothesis on the convection of lines of force that become opened during part of the daily convection cycle (Nishida, 1966).

In connection with the polar wind theory, we should like to turn attention to the following peculiarity of the polar ionosphere: amongst the results obtained in 1965 with the ion mass-spectrometer on OGO 2 at heights of 450–1500 km, besides the decrease in ion density to $\sim 10^2$ cm^{-3} and the depletion of light ions at latitudes of $>60°$, a changing though frequently existing peak was observed at $\gtrsim 80°$, in which the ion density increased by two orders of magnitude above the value at lower latitudes. This peak of ionization often has a rather high number of H^+ ions, and its electron component is systematically observed with radio methods (Thomas *et al.*, 1966). The lines of force corresponding to this polar peak of ionization are obviously open; the formation of this peak has evidently to be considered (particularly from the point of view of the polar wind). To what heights does this polar peak reach? It is difficult to answer this question, because direct measurements of the plasma in the polar region have not been made for heights above 3000 km.

The only spacecraft carrying instruments to measure the cold plasma, that passed, in 1962, through the regions of invariant geomagnetic latitudes $\Lambda \leqslant 72°$, at a geocentric distances of a few R_E was, as far as is known to us, the Soviet Mars 1 (Gringauz *et al.*, 1964). It registered significant ion densities in regions where, according to the model shown in Figure 3b, such densities ought not to exist.

Apparently, the phenomena related to cold-plasma distributions at great heights close to the equatorial plane have been studied far better than those at higher latitudes.

In concluding their article on simultaneous observations of the plasmapause made with the OGO satellite and at the Antarctic stations, Carpenter *et al.* (1969) wrote: "The results presented above may be deceptive in their simplicity. Data not presented here indicate that the plasmapause is extremely complex, with regions of irregular behavior, periods of rapid expansion or compression and variations in details of the plasma profile at the boundary. Further generation of correlation studies are needed to obtain a proper description of these effects."

It is necessary to keep these words in mind when using simple models of the plasmasphere, particularly when using them at comparatively high geomagnetic latitudes.

4. Energy of the Particles that Populate the Plasmasphere

4.1. INTRODUCTION

Charged particles with a great range of energies coexist in the plasmasphere, and it is only possible to study their energies using direct methods: as was already mentioned, observations of whistlers do not give any information on the energy of the particles.

The basic population of the plasmasphere consists of particles where energies do not exceed 1 eV by more than order of magnitude. This was shown in the experiments on the first lunar spacecraft (Gringauz *et al.*, 1960a). The particles in the radiation belts were also observed on these spacecraft (Vernov *et al.*, 1959) and a comparison of the results showed that the boundary of the plasmasphere (plasmapause in current terminology) was located inside the outer radiation belt, and that therefore, there were particles with subrelativistic and relativistic velocities in the regions under consideration as well as the cold-plasma particles.

The observations at comparatively low values of L of intense fluxes of electrons, with energies ranging from hundreds of eV to tens of keV (Frank, 1966), filled the gap in the energy distribution of charged particles in the plasmasphere between the 'cold' particles, and the high-energy particles of the radiation belts, and showed that particles with almost all energies, ranging from ~ 1 eV to hundreds of MeV, coexist in the plasmasphere.

The movement of these particles in the region close to the plasmapause, depends on their energies; the cold-plasma particles, because of their low velocities and corresponding small magnetic moment, do not drift due to the magnetic field gradient, but strongly react to the convective electric field; the charged particles of the radiation belts, whose motion is determined by the gradient drift to a considerable degree, react far less strongly to the electric field. The boundary of the forbidden zone formed by the convective electric field for the cold magnetospheric plasma is no obstacle for these high-energy particles. This does not mean that long-term effects of the electric field on the motions of the particles in the radiations belts can be neglected. For the fluxes of particles with intermediate energies ($E < 100$ keV) the convective electric field can cause a considerable asymmetry in the east-west direction (Axford, 1969; Tverskoy, 1970).

As was shown in the experiment carried out with electrostatic analyzers on the OGO 3 satellite (Schield and Frank, 1969), the plasmapause may be observed, not only in measurements of particles with energies of ~ 1 eV but also in measurements of electrons with energies of the order of hundreds of eV. We shall return to this later.

4.2. COLD PLASMA TEMPERATURE

The number of publications of experimental determination of the cold plasma temperature is small.

By comparing the ion currents from the four traps, which were mounted on each of the Luna 1 and Luna 2 satellite, in 1959, and which had different potentials on the outer grids, the ion temperature T_i of the cold plasma that surrounds the Earth was first defined roughly and it was determined that does not exceed a few tens of thousands of degrees (Gringauz *et al.*, 1960; Gringauz, 1961). Later publications, which contained experimental data for charged-particle temperature at geocentric distances of up to a few R_E, were based on measurements obtained using charged-particle traps with retarding potentials on the IMP 2 satellite (Serbu and Maier, 1966, 1967). These articles were critized a number of times because the authors, after reducing the first results, did not find the plasmapause (Gringauz, 1967; Binsack, 1967; Harris *et al.*, 1970).

According to the conclusions of Serbu and Maier, at a distance of $\sim 4\ R_E$, $T_e \sim 1$ eV; T_e increases with height according to the law $\sim R^2$, and T_e is considerably smaller than T_i. Because of the peculiarity of these results, which was pointed out (the absence of the plasmapause), it is difficult to determine which of the temperature data, obtained on IMP 2, refers to the plasmasphere, and which refers to the plasma outside of the plasmasphere. As was noted by Bezrukikh *et al.* (1967), an explanation of the causes for having $T_i \gg T_e$, is very difficult to find.

A method for determining T_i in the plasmasphere has been suggested, using current variations in a trap with a zero potential outer grid produced by spacecraft rotation (Gringauz *et al.*, 1967). Because of the insufficient amount of data obtained from the trap on Electron 2, only the upper limits of T_i were calculated, which for heights of $\leqslant 10000$ km for two passes of the satellite, turned out to be 7000° and 10000°, respectively (Gringauz *et al.*, 1967).

At a geocentric distance of $\sim 4.2\ R_E$, the upper limit of T_i was determined to be 1.1 eV (Bezrukikh *et al.*, 1967). These estimates were made before data on the orientation of the trap relative to the spacecraft velocity vector were obtained. Subsequently, using data from the solar orientation system of the satellite and the magnetometer, the orientation of the trap on Electron 2 relative to its velocity vector was determined, and corrections were made to account for some effects that had not been taken into account in the earlier estimation of the upper limit of T_i. This resulted in a lowering of the earlier estimate for the magnitude of T_i, from the Electron 2 data, by a factor of two.

The determination of electron temperature T_e, from the spherical Langmuir probe data from OGO 5, was complicated by photoemission. The authors of the experiment gave values for the magnitude ranging from 3×10^3 K at perigee (at a height of 300 km) to 3.5×10^4 K (close to the magnetopause). In calculating n_e inside the plasmasphere using the value $T_e = 10000$ K the experimenters estimated the error as being not greater than 50% (Freeman *et al.*, 1970).

4.3. ELECTRONS WITH ENERGIES 100 eV $\leqslant E \leqslant$ 50 keV IN THE PLASMASPHERE AND ON ITS BOUNDARIES

The possibility of detecting the plasmapause in electron energy distribution at energies of 100 eV $\leqslant E \leqslant$ 700 eV was demonstrated with the data from the electrostatic analyzer on the OGO 3 satellite (Schield and Frank, 1969).

Figure 13a shows measurements, made on the inbound pass of OGO 3 on 21 June, 1966, of the electron currents with the following energies: 80–100 eV curve no. (3), 190–330 eV (4), 310–540 eV (5), 410–720 eV (6), 640–1100 eV (7), and 990–1700 eV (8).

Figure 13b shows $n_e(L)$ profiles, constructed from Schield and Frank's data which were obtained from the same satellite pass, for electrons with energies in the range 100 eV $\leqslant E \leqslant$ 700 eV (dotted curve), and in the range 700 eV $\leqslant E \leqslant$ 50 keV (continuous curve).

The location of the peaks on curves (3)–(6), Figure 13a, and on the dotted curve on Figure 13b agree, to a good degree of accuracy, to the location of the plasmapause, as given by radio-frequency mass-spectrometer data that was obtained simultaneously on the same spacecraft. Schield and Frank note that the spatial distribution of electrons with energies of 100 eV $\leqslant E \leqslant$ 700 eV, is usually as shown in Figure 13.

There are cases, however, when the $n_e(L)$ profiles of electrons with energies in the given range do not show any change at the plasmapause. This usually occurs at times close to strong magnetic disturbances, when the region of trapped radiation becomes filled with low energy particles (with energies from a few hundred eV to tens of keV). This was, in particular, the case on 21 July, 1966.

The existence in the plasmasphere of rather sharp peaks in the density of electrons having energies in the range 100 eV $\leqslant E \leqslant$ 700 eV indicated that the interaction of the magnetospheric plasma that takes part in the convective motion, with ionospheric (plasmaspheric) plasma that corotates with the earth, may be accompanied by processes which are related to local heating of plasma, and which produce the accelerated electrons that are observed to have energies up to 700 eV.

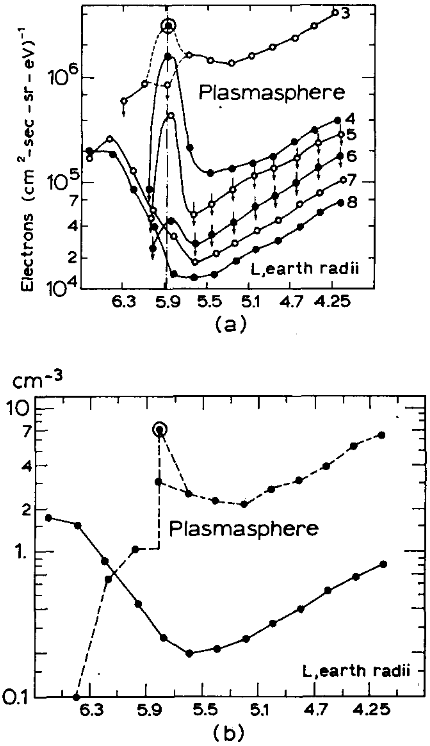

Fig. 13. (a) Electron fluxes with energies of 80–100 eV (3); 190–330 eV (4); 310–540 eV (5); 410–720 eV (6); 640–1100 eV (7); 990–1700 eV (8). (b) $n_e(L)$ profiles for electron energies of – – – – 100 eV $\leqslant E \leqslant$ 700 eV, – – – – – 700 eV $\leqslant E \leqslant$ 50 keV (according to the data of Schield and Frank, 1969).

5. Conclusions

Although the first articles on the observation of the plasmapause did not attract the attention of many geophysicists (in the first six years from 1960 to 1965 the number of articles on the plasmasphere was less than 10) the situation has changed considerably in the past five years.

Theoretical papers have appeared, dealing specifically with the formation of the plasmapause (Block, 1966; Nishida, 1966; Samokhin, 1967a, 1967b, 1969; Brice, 1967; Mayr, 1968; Kavanagh *et al.*, 1968; Raspopov, 1969a, 1969b).

The reduction of observational results of whistlers and direct plasmaspheric measurements from the Electron 2 and 4 satellites, and the OGO 1, 3 and 5 satellites have given a great wealth of information, and the results of the direct and indirect measurements are in good agreement in the equatorial plane (although at higher geomagnetic latitudes, the situation is less clear).

It has become generally agreed that the plasmapause is related to the important ionospheric and magnetospheric phenomena.

The propagation of very-low-frequency radio waves (Helliwell, 1969, 1972), the peculiarities of the polar ionosphere structure (Thomas *et al.*, 1966; Taylor *et al.*, 1968b), the heating of the night side of the F region of the ionosphere (Nagy *et al.*, 1968), the generation of micropulsations in the geomagnetic field (Troitskaya and Gul'elmi, 1969), the basic current systems in the ionosphere, large-scale electric fields and the convection of cold plasma in the magnetosphere (Axford, 1969) – all these phenomena have proved to be related in one way or another to the plasmasphere or plasmapause.

With the help of empirical relations connecting the K_p index to both the solar wind velocity, and to the plasmapause location, it is possible to determine roughly the convective electric field along the evening meridian (Vasyliunas, 1968b).

The measurements of the plasmapause made in the morning sector are most convenient for investigation of the large-scale electric field in the magnetosphere (Raspopov, 1969b).

Evidently, measurements of plasmapause position and the use of these results for the estimation of the electric field in the magnetosphere allows the theory of large-scale variations in the radiation belts to be defined more exactly (Tverskoy, 1972).

All this allows one to foretell, (with no danger of being mistaken), that the study of the plasmasphere, and in particular, the plasmapause, will be significantly widened in the near future.

This is all the more necessary because many of the characteristics of the processes taking place near the plasmapause are not clear; experimental data on the cold plasma close to the earth at $R \geqslant 1.4\ R_E$ over high latitude regions are very meagre and, in particular are entirely lacking above the polar peak of ionization.

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