Radiophysics and Quantum Electronics , Volume 12, Number 9, 999-1023, 1969

THE LOW-ENERGY MAGNETOSPHERIC PLASMA – A SURVEY

K. I. Gringauz

UDC 533.9 : 550.3

INTRODUCTION

The space round the earth is filled with charged particles whose distribution significantly affects the propagation of low-frequency radiowaves. The overwhelming majority of the particles are comparatively low-energy ($\lesssim$ 50 keV) electrons and ions; the densities and energy fluxes of the subrelativistic and relativistic particles which make up the radiation belts are considerably smaller than those of the low-energy plasma; in practice these particles are unimportant from the point of view of radiowave propagation and do not have any significant effect on such geophysical phenomena as auroras or magnetic and ionospheric storms.

It will be seen that the mapping of the low-energy plasma distribution in the magnetosphere, which is very important for understanding the interaction of electromagnetic waves and particles, is still far from complete.

Experiments on earth satellites and other spacecraft during the last decade have led to substantial changes in our ideas of the physical properties of near-earth space, which had previously been based on many years of ground observations. In particular, the size of the earth's plasma sheath – the ionosphere – which consists of very low-energy (thermal) particles, turned out to be much bigger than anticipated. The radiation belts were discovered. It was found that the shape of the geomagnetic field at great distances from the earth in the direction of the sun differs markedly from that of a dipole and that in the antisolar direction it loses all resemblance to it, forming a magnetic tail which stretches for many hundreds of earth radii.

All these recently discovered phenomena are closely connected with geomagnetic disturbances caused by the interaction of the earth's field with the solar wind; this interaction sets up a complicated distribution of charged particles near the earth with velocities ranging from thermal to relativistic values. The spatial distribution of these charged-particle fluxes is to a great extent determined by the structure of the magnetic field near the earth and in turn strongly affects the shape of this field (especially at geocentric distances of ~(7–10)R_e, where R_e is the radius of the earth).

The height of the region at about $4R_e$, for which there is a sharp drop in the charged-particle density of the cold plasma sheath, as discovered in 1959 (Gringauz et al., 1960a; Gringauz, 1961a), turned out to depend strongly on geomagnetic activity (Carpenter 1963, 1966a).

After the discovery in 1958 of clearly defined radiation belts during the experiments designed to study cosmic rays (Van Allen, 1958; Vernov et al., 1958) it seemed that the outer boundary of the belts [~ (7–8)R_e in the equatorial plane] was also the limit of the near-earth space. The trapped-radiation zone was thought at that time to be symmetric about the geomagnetic dipole [the variations with local time were only discovered at the end of 1961 (O'Brien, 1963)].

So, when in 1959 it was found from Soviet lunar flights designed to study the interplanetary plasma that outside the outer radiation belt there were regions with considerable fluxes of low-energy electrons (E > 200 eV) which had not been recorded by the cosmic-ray counters, it was naturally assumed that there was a third radiation belt consisting of very soft electrons, similar in shape to the outer belt but differing in the lower energy and higher flux values (Gringauz et al., 1960a; Gringauz et al., 1960b). In 1961 this

Radio Engineering Institute, AS USSR. Translated from Izvestiya VUZ. Radiofizika, Vol. 12, No. 9, pp. 1275-1310, September, 1969. Original article submitted February 7, 1969.

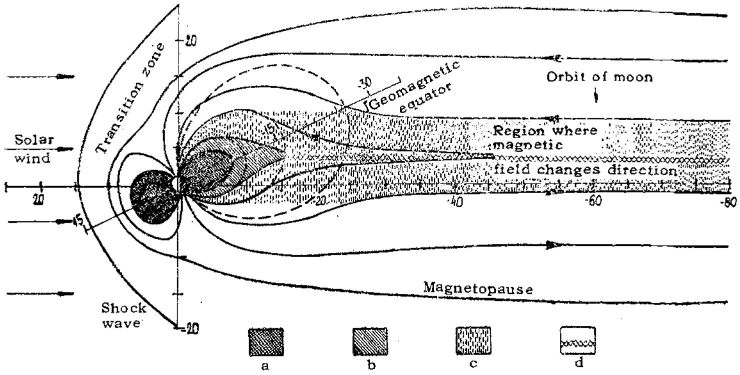

Fig. 1. Structure of the geomagnetic field disturbed by the solar wind (earth's magnetosphere in the magnetic meridian plane; Hess, 1967): a) radiation belts; b) cape region; c) plasma layer; d) neutral sheet.

zone was named the outermost charged-particle zone (Gringauz, 1961); it was not realized at the time that the properties of the fluxes varied with local time.

It is now known that the low-energy electron fluxes beyond the outer belt in the midday direction belong to the unstable radiation zone which stretches up to the magnetospheric boundary, and to the partially thermalized solar plasma behind the shock front which arises from the interaction between the supersonic solar wind and the geomagnetic field. The fluxes on the midnight side are observed in the unstable radiation zone and in the plasma layer of the magnetotail which contains the neutral sheet. When these electron fluxes were first discovered, however, the real difference between the midnight and midday structures of the earth's field outside the radiation belts [i.e., at $\sim (7\text{-}10)R_e$] was unknown. The current representation of the structure of the magnetosphere is shown in the recent diagram of Fig. 1 (Ness, 1967).

The present survey makes frequent reference to this diagram; it should be pointed out, however, that although the figure shows several charged-particle zones, it does not depict the full distribution in the magnetosphere (it was apparently not the author's intention to do so). Thus, it does not show the plasma sheath surrounding the earth – the ionosphere – which is made up of very low-energy (thermal) particles and which contains a boundary which crosses inside the energetic trapped-radiation zone (more exactly, inside the outer radiation belt). Again, while the radiation belt on the night side is shown surrounded by plasma, on the day side no plasma is indicated beyond the belt, though in fact it does exist in the unstable radiation zone and farther out in the transition layer beyond the magnetospheric boundary.

It is quite clear that the stable field structure with the enormous elongation in the antisolar direction shown in Fig. 1, which was so unexpected by the ideas of the fifties, is the result of the superposition on the earth's dipole field of another field from some fairly stable system of electric currents. It is also obvious that these currents cannot be created by the fluxes of charged particles with $E < 50$ keV in the radiation belts, because these are comparatively close to the earth and the field is still almost dipole; moreover, the kinetic energy of the particles per unit volume ($\Sigma mv^2/2$) is only a small fraction of the magnetic field energy $B^2/8\pi$. The currents should however be formed by the comparatively low-energy ($E < 30\text{-}50$ keV) charged particle fluxes which exist beyond the radiation belts.

It is, in fact, these fluxes which apparently "top-up" the radiation belts and become all-important in causing auroras and other related phenomena; for this reason, several authors have called them "auroral radiation." Dessler and Juday (1965) used this name for the low-energy plasma which enters the polar regions from the magnetotail and is connected with the neutral sheet. O'Brien (1966, 1967) extended this idea to include the charged-particle fluxes in the day and night parts of the unstable radiation zones, i.e., $8 < L < 10$.*

Low-energy charged-particle fluxes also exist inside the radiation belts, though they are very variable in time; they sometimes exceed the much more stable high-energy particle fluxes (Gringauz et al., 1965, 1966a; Pizella et al., 1966) and can cause magnetic storms (Frank, 1967).

* For the use of the coordinate L, see below.

It follows from this that the study of the low-energy plasma is one of the main problems in magnetospheric physics; the principal features of the magnetosphere and the main events which occur in it are determined by the distribution of this plasma, by its properties and behavior (all of which in turn depend on the solar wind). This survey considers the low-energy plasma (energies from thermal up to about 45 keV) in the various regions of the magnetosphere, in order of increasing distance from the earth. The main emphasis is on experimental results.

Despite the importance of this subject, it has developed much more slowly than the study of high-energy trapped radiation. This is partly explained by the difficulty in making instruments to record low-energy charged particles because of the necessity of excluding the effects of solar ultraviolet rays and the secondary effects of hard radiation.

In the first years after the discovery of the low-energy plasma in the magnetosphere, the investigation was carried on using "integral" instruments which showed only that the particle energies lay between hundreds of electron volts and the lowest values recorded by the high-energy counters (Gringauz et al., 1960; Gringauz et al., 1964; Freeman, 1964); in recent years measurements have been made to determine the particle energies much more accurately (Vernov et al., 1965, 1966; Wolfe et al., 1966a, 1966b, 1967; Bame et al., 1967; Frank, 1967a, 1967b; Vasyliunas, 1968b).

The experimental results on low-energy fluxes and the interpretation of particle problems during the last few years (1965-1968) are discussed in a series of survey articles and in introductions to original papers (Bezrukikh and Gringauz, 1965; Taylor et al., 1965; Gringauz and Khokhlov, 1965; Carpenter, 1966; O'Brien, 1967; Dungey, 1967; Ness, 1967; Binzack, 1967; Frank, 1967a; Vasyliunas, 1968b; etc.).

This survey represents an attempt at a short summary of the information published before the Washington Symposium.* Space does not allow a discussion of the problems of recording low-energy cosmic particles, although these are undoubtedly of great interest.

We shall make use of the magnetic shell parameter L introduced by McIlwain (1961); for a dipole field this is equal to the distance from the center of the earth to the magnetic shell expressed in units of R_e. For high latitudes (with L > 8-10), this parameter is devoid of meaning since the geometry of the real field corresponds to the picture of Fig. 1. However, many authors, in presenting experimental results, use L even for values greater than 10 and we shall do the same.

In Table 1 we give some of the characteristics of satellites which have flown through the magnetosphere with instruments designed for studying the plasma and which are mentioned again below.

1. THE EARTH'S PLASMA SHEATH (OUTER IONOSPHERE)

It is sensible to start with terminology. This section will deal with the region up to 20,000-30,000 km in height, which is filled with thermal electrons and protons (energies not exceeding a few electron volts).

In the literature (as has been pointed out before, Gringauz, 1967), many different names have been used for this region: "the ionized component of the geocorona" (Gringauz et al., 1960); "the protonosphere" (for example, Heisler and Bowhill, 1965); "the magnetosphere" (Taylor et al., 1965); "the plasmasphere" (Carpenter, 1966); "the outer ionosphere" (Gringauz, 1966). When the electron or ion densities are measured by means of rockets from 1500-2000 km upwards (i.e., from ionospheric heights), no singularities are detected right up to the region where the density begins to decrease rapidly (the "knee"). In other words, there is no boundary between the normal ionosphere and the region under discussion. Indeed, no attempts have ever been made even to define a conventional boundary. Therefore, although the term "plasmasphere" is becoming more and more popular, "the outer ionosphere" seems to me a more appropriate name.

There have been a number of observations of both ion and electron components of the outer ionosphere. It is now possible to discuss with some certainty its physical properties, and in particular, the existence (at least at temperate geomagnetic latitudes at distances of ~ $3R_e$ to ~ $6R_e$) of a region where there is a sharp break (drop) in the height variation of charged-particle concentration (the so-called "knee"). We shall take the boundary of the outer ionosphere to be the limit of the region below the knee and call it the "plasmapause" (after Carpenter, 1966).

* International Symposium on the Physics of the Magnetosphere, September 3-13, 1969.

TABLE 1

Spacecraft	Date of launch	Apogee (km)	Perigee (km)	Inclination	Instruments for detecting low-energy plasma
1. Luna 1	1/2/1959				Charged-particle traps
2. Luna 2	9/12/1959				Charged-particle traps
3. Explorer 12	8/16/1961	83,600	6700	33°	CdS detector; spherical electrostatic analyzer
4. Alouette 1	9/29/1962	1000 (circular orbit)		80°	Ionospheric sounder; ELF radiation receiver
5. Explorer 14	10/2/1962	85,300	300	33°	Spherical electrostatic analyzer
6. Mars 1	11/1/1962	Interplanetary station			Charged-particle traps
7. Injun 3	12/13/1962	2785	237	70.4°	Electron multiplier
8. IMP 1	11/27/1963	191,230	197	33°	Charged-particle trap (analyzer with retardation potential and modulation-type Faraday pan). Spherical electrostatic analyzer
9. Élektron 2	1/30/1964	68,200	460	61°	Charged-particle trap. Electrostatic analyzer
10. Élektron 4	7/11/1964	66,235	460	61°	Charged-particle trap; spherical electrostatic analyzer
11. Vela 2B	7/17/1964	115,140	90,920	40°	Spherical electrostatic analyzer
12. OGO 1	11/5/1964	150,000	280	31°	Faraday pan (modulation-type charged-particle trap); spherical electrostatic analyzer
13. IMP 2	10/4/1964	93,910	197	33°	Charged-particle trap; analyzer with retardation potential and modulation-type Faraday pan; spherical electrostatic analyzer
14. Explorer 22	10/19/1964				Cylindrical Langmuir probe; ionospheric sounder
15. Injun 4	11/21/1964	2495	530	81°	Scintillation counter for energy flux
16. Zond 2	11/30/1964	Interplanetary station			Integral and modulation-type charged-particle traps
17. Vela 3A	7/20/1965	115,840	106,370	35°	Spherical electrostatic analyzer
18. Vela 3B	7/20/1965	122,080	100,570	34°	Spherical electrostatic analyzer
19. Alouette 2	11/29/1965	2980	500	80°	Ionospheric sounder
20. Luna 10	3/31/1966	Moon satellite			Ion trap; electron trap; trap for recording thermal ions, modulation-type Faraday pan
21. OGO 3	6/7/1966	122,300	295	31°	Modulation-type charged-particle trap; four cylindrical electrostatic analyzers
22. Explorer 33	8/17/1966	440,000	50,000	7°	Modulation-type charged-particle trap

TABLE 1 (continued)

Spacecraft	Date of launch	Apogee (km)	Perigee (km)	Inclination	Instruments for detecting low-energy plasma
23. Pioneer 7	8/17/1966	Interplanetary station			Modulation-type charged-particle trap; quarter-sphere analyzer
24. ATS 1	12/7/1966	Synchronous orbit 35,800			Trap for recording thermal ions
25. Explorer 35	7/19/1967	Moon satellite			Modulation-type charged-particle trap

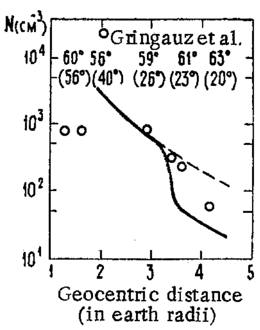

Fig. 2. Electron density n_e (from whistler atmospherics) and ion density n_i (Luna 2 data) as functions of geocentric distance. The invariant and geomagnetic (in parentheses) latitudes intersected by Luna 2 are shown at the top of the figure (Carpenter, 1963).

The first direct measurements of positive ion densities in the outer ionosphere were made in 1959 by means of the charged-particle traps on board the Soviet moon rockets Luna 1 and Luna 2 (Gringauz et al., 1960; Gringauz, 1961). The experiments discovered the existence at heights of ~ 20,000 km (R ~ $4R_e$) of a region of increased rate of fall in charged-particle concentration, a sort of "plateau" in the height distribution, and gave the first rough estimate of the ion temperature T_i at $4R_e$ (namely, that T_i was not greater than some tens of thousands of degrees).

A very important stage in the study of this region was the discovery of the knee in the equatorial height distribution of the electron density n_e from the analysis of whistler propagation data (Carpenter, 1963). This work was the beginning of a series of studies by Carpenter and his colleagues, which produced valuable statistical data showing the height variations of the knee in the outer equatorial ionosphere as a function of local time and geomagnetic activity.

Figure 2, which is taken from the first publication by Carpenter (1963), shows an n_e profile obtained from whistler data; the open circles denote the values of ion density n_i determined in 1959 from Luna 2. Carpenter considered the agreement between these data to be satisfactory.

In discussing the difference between the Luna-2 data and Carpenter's results, Obayashi (1964) pointed out that a possible cause of the discrepancy might be the difference in geomagnetic latitudes at which the studies were made. The ionospheric temperature vs height curve can vary strongly with latitude — at high latitudes the temperature might be larger because the thermal conductivity of the ionosphere is extremely anisotropic; this can affect the height distribution of charged-particle density. Carpenter and Smith (1964) noted that the discrepancy between the equatorial-plane n_e profile in Fig. 2 and the Luna-2 data might be due to the decrease in density with latitude at comparatively low heights since the n_i measurements started at ~ 2000 km at a geomagnetic latitude of 60°.

Carpenter (1966) subsequently reduced a vast amount of experimental data on whistlers recorded at high-latitude stations in the Antarctic and involving hundreds of thousands of sonograms. Figure 3 shows the averaged data on the position of the knee in the geomagnetic equatorial plane for days of moderate activity (K_p = 2-4).

The dashed line shows the position of the knee from 1500 LT on July 28 through 0430 on July 29, 1963. The curve depicting the average diurnal variation of the knee (plasmapause) for days of moderate activity has the following properties:

1. The smallest geocentric distance (3-3.5R_e) is observed in the morning around 0600.

2. At about 1800 there is a rapid increase in the height of the knee with R changing from 3.5 to 5. The return movement is much slower and lasts about 10 h.

3. From 0600 to noon, the height increases smoothly.

In the first references to the plasmapause, it was noted that its height depended strongly on the level of geomagnetic disturbance (Carpenter, 1963; Carpenter and Smith, 1964). The details of this dependence

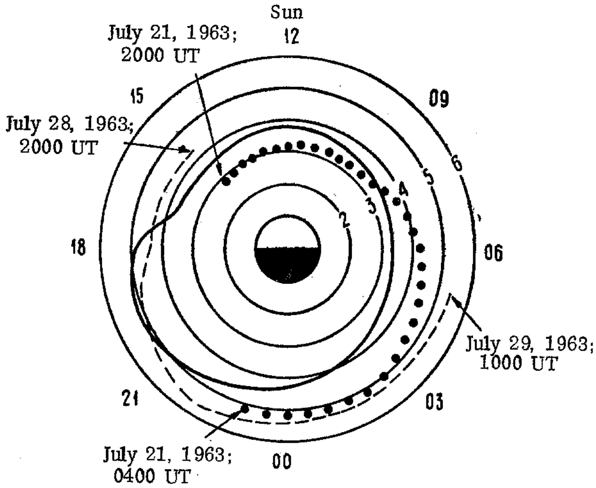

Fig. 3. Measured position of plasmapause as a function of local time. The numbers show the values of R in units of R_e. The dotted curve corresponds to increased magnetic activity, and the dashed curve to decreased activity (Carpenter, 1966).

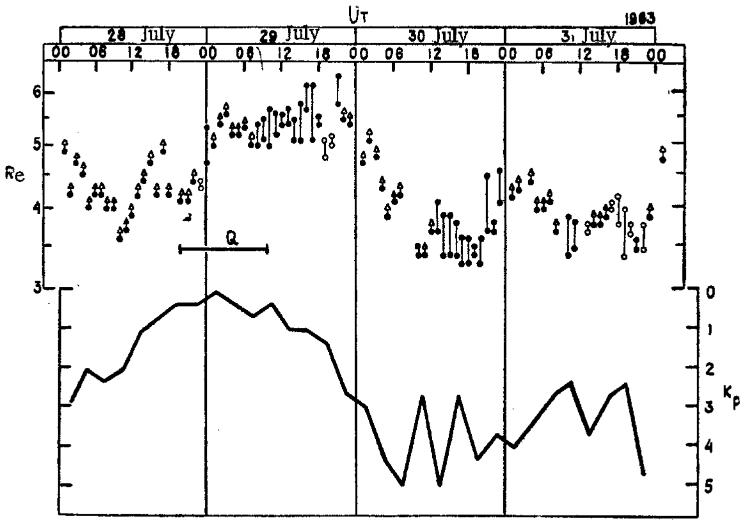

Fig. 4. Position of the plasmapause as a function of geomagnetic activity for the period July 28–31, 1963; universal time (Carpenter, 1966).

were published later (Carpenter, 1966). An example is shown in Fig. 4, from which it can clearly be seen that an increase in disturbance brings the knee closer to the earth. The author pointed out that a change in activity is, as a rule, followed 6 h later by the change in height.

An analysis of the vast whistler data, taken together with the ion mass-spectrometer results (Taylor et al., 1965) described below, enabled Carpenter to propose a preliminary model of the distribution of the thermal plasma round the earth. In this model, the earth is surrounded by a plasma sheath which rotates together with it. For moderate geomagnetic activity, the projection of this sheath on the equatorial plane describes a circle (Fig. 3) (apart from the 1700-2400 LT section). With increased activity, the sheath contracts and becomes more asymmetrical; as K_p decreases, the opposite occurs.

Figure 5 shows an idealized meridian projection of the daytime part of the plasma sheath (~ 1400 LT). The shaded region is bounded by the magnetic shell L = 4 and corresponds to $n_e = 10^2$ cm^{-3}; outside this

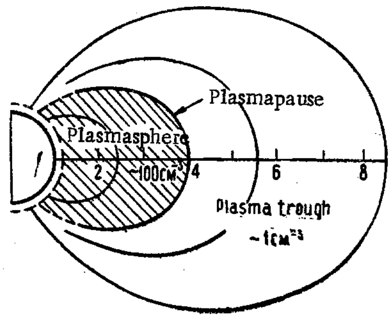

Fig. 5

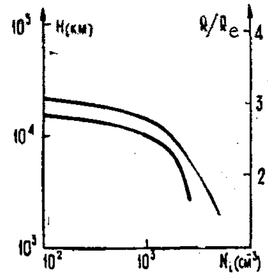

Fig. 6

Fig. 5. Model of the distribution of thermal plasma in a meridian section of the magnetosphere at about 1400 LT (moderate geomagnetic activity, K_p = 2-4) (Carpenter, 1966).

Fig. 6. Height distribution of ion density (n_i) in a region close to the magnetic equatorial plane; data from charged-particle traps on Élektron 2 (Bezrukikh and Gringauz, 1965).

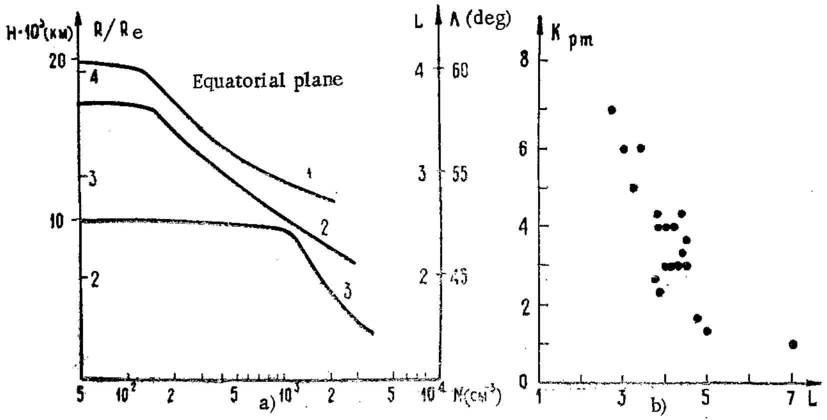

Fig. 7. a) Ion density n_i as a function of height H, geocentric distance R, and L-coordinate (nighttime, January-February, 1964); data from Élektron 2 (Bezrukikh, 1968): 1) 31.01,1964, $K_{pm} = 3_0$; 2) 12.02,1964, $K_{pm} = 4_0$; 3) 14.02, 1964, $K_{pm} = 5_0$. b) Relation between position of the knee in L-coordinates and the maximum K-index in the course of the day preceding the measurements; data from Élektron 2 and Élektron 4 (Bezrukikh, 1968).

region, $n_e \sim 1$ cm^{-3}. Carpenter suggests that during low magnetic activity the field line L = 4 represents a fairly sharp boundary. Nearer the earth, however, the difference between the n_e on the two sides of the boundary can get considerably smaller. In Fig. 5 this part of the field line is shown dashed. The average of all the whistler data (Carpenter, 1966) obtained during moderate activity has shown that the height distribution has a sharp break at distances of about $4R_e$ both during the day and at night. While at night, however, the change in n_e is 30-100 times in a distance of $0.15R_e$, during the day it was reduced to ten times.

Measurements of the ion component of the thermal plasma by means of charged-particle traps, which started on the Soviet lunar craft in 1959, were continued in 1964 in the Élektron series of satellites. Some preliminary results, obtained on Élektron 2 and referring to the equatorial regions of the outer ionosphere, were published in 1965 (Bezrukikh and Gringauz, 1965; Gringauz et al., 1966): more detailed results are given by Bezrukikh (1968). Figures 6 and 7 show examples of the results obtained from measurements made by the Élektron satellites. It can be seen from Fig. 7 that conclusions similar to those of Carpenter may be drawn from these data.

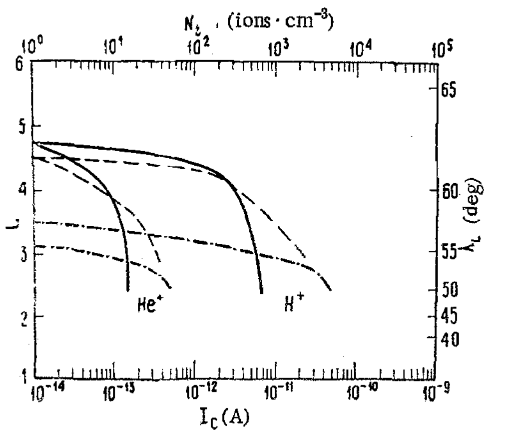

Fig. 8. Proton and helium ion density as a function of the coordinates; mass-spectrometer data from OGO-1 (Taylor et al., 1965). Continuous line — November 2, 1964. Dashed line — November 10, 1964. Dash-dot line — November 26, 1964.

The ion components of the outer ionosphere have also been studied by means of Bennet radiofrequency mass spectrometers on satellites OGO-1 and OGO-3 (Taylor et al., 1965; Taylor et al., 1968). On these satellites the position of the plasmapause was obtained by means of charged-particle trap plasma detectors (Vasyliunas, 1968). In addition, traps were used to obtain data on the outer ionosphere in IMP-2 (Serbu and Maier, 1966a, 1966b; Binzack, 1967).

Figures 8 and 9 give some results of the ion mass-spectrometer measurements made on OGO-1 (Taylor, et al., 1965). The results showed that in the overwhelming majority of cases, the plateau in the height variation of n_i gets lower during periods of high magnetic activity and vice versa. This compression of the outer ionosphere during disturbed periods is studied in Taylor et al. (1968) in connection with the OGO-1 and OGO-3 data for 1965-66. The authors conclude that there is a negative correlation between the L-coordinate of the plasmapause at any time and the maximum value of K_p in the preceding 24 h. During the solar flare events of July 15, 1965 and June 7-9, 1966, when K_p was equal to 5, the plasmapause descended from L = 6 to L = 3.3.

During the flight of OGO-1 and OGO-3, Carpenter, Park, and Taylor (1968) made several simultaneous measurements of the knee by three independent methods: analysis of whistlers recorded in the Antarctic; ion spectrometer measurements on the satellite; and ELF measurements on board. In the last method the crossing of the plasmapause is distinguished by a sudden change in the nature of the received ELF signal. The observed L-values of the knee lay within the limits 3.2–5.5. Simultaneous measurements made on board and on the ground and corresponding to a local time difference of about 1 h gave the same position for the plasmapause (within the experimental error limits of $\pm 0.2 R_e$). The results from the mass-spectrometer and ELF experiments agreed to within about $0.1 R_e$.

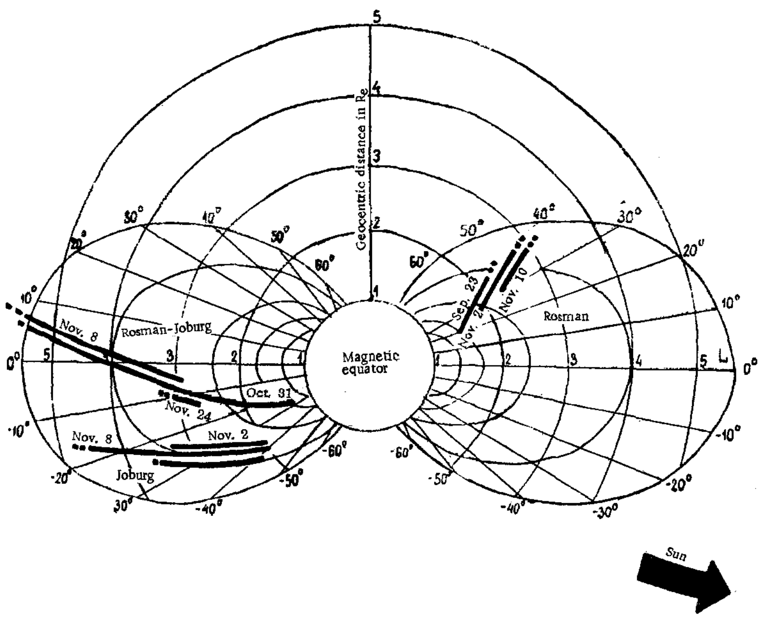

Fig. 9. Sections of the OGO-1 orbits on which reductions in ion density were observed. The continuous part of each line corresponds to a uniform decrease in density with height; the start of the dashed line shows the position of the sharp fall in current (Taylor et al., 1965).

These experiments show that both ground-based whistler observations and satellite measurements are reliable. They also provide evidence that the plasmapause (at least in moderate latitudes) does in fact have the shape of a geomagnetic sheath.

The OGO-1, OGO-3, and IMP-2 satellites also had MIT plasma detectors designed to record electrons (Binzack, 1967; Vasyliunas, 1968). An analysis of the readings of these instruments and of the characteristics of the recordings showed that as a result of certain secondary processes, which we will not discuss here, they reliably detected the instants when the satellites crossed into regions of high positive-ion concentration, i.e., the entrance to the plasmapause. A comparison between the changes in the position of the plasmapause and the variations in magnetic activity led the authors to conclusions similar to those of Carpenter and Taylor et al. In particular, Binzack takes the plasmapause under quiet conditions to correspond to L = 6 and for other values of K_p to be given approximately by the empirical equation

$$\Delta = 6 - 0.6K_p,$$

where the K_p index refers to the time of observation.

It should be noted that the IMP-2 satellite made simultaneous measurements with charged-particle traps of both the electron and ion components of the plasma sheath; the particle energy was analyzed by the retarding-potential method (Serbu and Maier, 1966a, 1966b). In their interpretation of the data, the authors did not discover a knee in the charged-particle distribution. We have pointed out before (Gringauz, 1967) that this contradicts a number of separate independent observations. Indeed, it is even in contradiction to the simultaneous measurements made on the same satellite (Binzack, 1967). The cause of these discrepancies needs to be determined.

Serbu and Maier concluded from the IMP-2 results that for $4R_e < R < 10R_e$, the ion temperature is considerably higher than the electron temperature ($T_e \sim$ 1-2 eV, $T_i \sim$ 4-8 eV). These values of T_i are much greater than the upper estimates for $R < 5.5\ R_e$ from the Élektron-2 data (Bezrukikh et al., 1967). It follows from theoretical models of the outer ionosphere (Heisler and Bowhill, 1965; Gliddon, 1966; Bauer, 1967) that in the absence of any selective heating or cooling sources for the electron and ion gases, T_i should not exceed T_e; no satisfactory mechanism for selective heating has been discovered. Investigations of the lower ionosphere made in recent years have shown that the geomagnetic field exercises a large measure of control over its behavior. A number of ionospheric properties which are connected with the transport of charged particles along magnetic tubes of force are discussed in the survey by Roederer (1967) on conjugate-point phenomena. Considerable latitude gradients have been found at high latitudes. These are connected with the trough in electron density which has been observed at heights between 1000 km and the F_2 layer maximum on Alouette-2 ionograms (Thomas et al., 1964), and also at a height of $\sim$ 1000 km on the Langmuir probe results from Explorer 22 (Brace and Reddy, 1965). Strikingly small values were found from high-latitude Alouette-2 ionograms at heights of 1500-3000 km, where for $L > 6$, n_e varied from 8 to 100 cm^{-3}, and the boundary of the $n_e = 30\ cm^{-3}$ region was found to move in geomagnetic latitude from midday to midnight by 8° (Hagg, 1967). The authors of these experiments note the similarity between these high-latitude effects at low heights and the knee which is observed at great heights at low latitudes. Although the relation between these effects seems to us indisputable, it cannot serve as a complete explanation of the existence of the knee, if only for the reason that the low-altitude phenomena at high latitudes are themselves still in need of explanation. Moreover, as Angeramy and Carpenter (1966) have noted, there is some disagreement between variations in the position of the knee in the equatorial plane and changes in the lower ionosphere at high latitudes.

In 1961, the Axford and Hines theory of high-latitude geophysical phenomena and magnetic storms was published; a model of the magnetosphere was put forward in which the outer layers contained a plasma in convective motion. The source of the motion was taken to be the viscous-type interaction between the magnetospheric plasma and the solar wind. As a result of the plasma motion in a magnetic field, electric fields are set up. Near the geomagnetic dipole a forbidden zone is created into which the convecting plasma cannot penetrate; the size of this zone is defined by a geomagnetic latitude of 62°, which corresponds in the equatorial plane to $\sim 4.5R_e$. It is quite clear that the form of the variation of plasma density with distance must be different inside and outside the forbidden zone.

In the same year, another model was suggested with the convecting plasma motion being caused by the joining-up of the field lines in the magnetotail with those of the interplanetary field (Dungey, 1961).

Thus, soon after the publication of the first experimental results from moon rockets on the plasma density at a few earth radii, independent theoretical arguments appeared which predicted the existence of a break in the plasma distribution at about $4.5R_e$. There then appeared a series of theoretical papers in which the common feature was the acknowledgement of the existence of convection and of a forbidden zone and in which the boundary of this zone was directly identified with the knee (Block, 1966; Nishida, 1966; Dungey, 1966; Samokhin, 1966, 1967, 1967a, 1968; Kavanagh et al., 1968; Brace, 1967). These papers differ in their choice of the cause of convection and of the forbidden zone and in the configuration of the postulated magnetospheric electric field; in some the rotation of the earth is of essential importance, in others it is ignored. Nevertheless, the convective plasma motion remains one of the main features of all the models.

Until recently, of course, ideas about the convective circulation were based on indirect data (ground-based drift observations of aurora and radio scintillations, high-latitude geomagnetic disturbances, and so on); lately, however, measurements from the geostationary ATS-1 satellite seem to have produced direct experimental evidence (Freeman, 1967; Freeman et al., 1968; Freeman and Young, 1968). A movement of the thermal magnetospheric ions ($E \sim 1$ eV) at ~ 30 km $\cdot$ sec^{-1} has been established. The authors estimate that this corresponds to an electric field of ~ 5 mV $\cdot$ m^{-1} directed across the magnetosphere from the morning to the evening side.

In the Dessler and Michel model (1966), the variation of plasma density is explained without recourse to convective motion in terms of the evaporation of plasma from the polar ionosphere along the field lines of the open magnetotail. In the latest papers of Axford (1968) and Banks and Holzer (1968) arguments and numerical calculations are given in favor of a supersonic effusion of plasma from the polar ionosphere (called by the authors "the polar wind") which could also serve to explain the existence of the knee. A discussion of these papers could well form the subject of a special survey on its own and we hope to attempt this in a subsequent report.

In conclusion, the sum total of the available experimental data on the cold (thermal) magnetospheric plasma shows that there is a characteristic surface – the boundary of the outer ionosphere or plasmapause – which apparently divides the part of the plasma which is in convective motion from the part of the plasma which is in convective motion from the part which rotates with the earth. The plasmapause is situated inside the outer radiation belt; it contracts (gets closer to the earth) with increased magnetic activity and expands with decreased activity.

If we use the Carpenter (1966) model, as defined in the equatorial (Fig. 3) and meridian (Fig. 5) planes, we must bear in mind the following points:

1. The method used to obtain the electron density from whistler data gives n_e only in the equatorial plane.

2. In constructing the cold plasma sheath model in the meridian plane, Carpenter relied partly on the results of Taylor et al. (1965) from OGO-1. However, the orbit of this satellite, like those of IMP-2 and OGO-3, had a comparatively small inclination, and so the data obtained refer to geomagnetic latitudes $\lesssim 45°$. It was for this reason apparently that the author stated that the dashed part of the boundary field line in the figure corresponds to a region where the shape of the knee is not sufficiently well established.

It should be noted that in the charged-particle profiles obtained in 1964 with traps on Élektron 4, those for which there is no clearly distinguishable knee are those corresponding to latitudes > 45° (Bezrukikh, 1968). It must also be remembered that the OGO positive-ion densities are accurate to within a factor of 5 only because of the difficulties in reducing the values of current to particle densities (Taylor et al., 1965); similar difficulties were met in the analysis of the Élektron data (Bezrukikh and Gringauz, 1965). Therefore, the Carpenter model must be approached with some caution and not be considered as final, especially in view of the fact that the author himself calls it "preliminary."

2. LOW-ENERGY ($E \lesssim 40$ keV) PARTICLE FLUXES IN THE TRAPPED-RADIATION ZONE

Early estimates of the particle fluxes in the radiation belts by the authors of the first American and Soviet experiments were much too high; on the other hand, the energies were taken as too small. The electron flux in the outer belt was considered to be 10^{10}–10^{11} cm^{-2} $\cdot$ sec^{-1} at energies of E > 20 keV. These

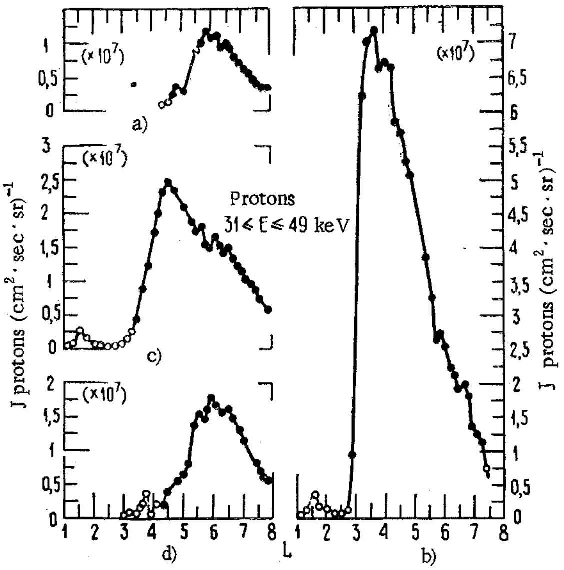

Fig. 10. Values of the proton (E < 50 keV) flux as a function of the L-coordinate during a magnetic disturbance; data from electrostatic analyzer on OGO-3 (Frank, 1967): a) July 7, 1966, pre-storm; b) July 9, main phase; c) July 11, recovery phase; d) July 13, post-storm. ●●● show intensity; ○○○ show upper limit.

estimates were connected with the fact that, in order to interpret the instrument readings, it was necessary to make some insufficiently established assumptions about the particle energy spectrum. Despite the fact that the Luna-2 data had shown that the total electron flux in the outer radiation belt could not exceed $2 \cdot 10^7$ cm^{-2} · sec^{-1} (Gringauz et al., 1960; Gringauz et al., 1963), other experiments before 1962-63 accepted values three orders of magnitude greater. Such large fluxes led many authors to believe that the energetic charged particles trapped in the outer belt could be the cause of magnetic storms and that their dumping into the atmosphere could directly produce auroras.

When the reduced estimates of the electron fluxes and the harder-energy spectrum became widely accepted, interest in the outer radiation belt as the cause of important geophysical phenomena weakened considerably. It is apparently increasing again, now that it has been established that in the outer belt there are low-energy electron fluxes which vary strongly with time and which have an energy density that sometimes becomes quite considerable.

We begin with a look at the inner belt ($L \lesssim 2$). Reports on the low-energy plasma flux here are few in number. Freeman (1962) interpreted the Injun-1 CdS results at a height of ~ 1000 km at L > 1.7 as evidence of protons with energy 0.5 keV < E < 1 Mev, carrying an energy flux of 50 ergs · cm^{-2} · sec^{-1}.

Frank and Swisher (1968), using data obtained in 1966 from an electrostatic analyzer in OGO-3, noted that for L < 1.7 the maximum energy fluxes of recorded protons (100 eV-50 keV) was 10-100 times smaller than the value given by Freeman. They also pointed out that an analysis of the 1965 Injun-4 results (unpublished) showed that for protons with E > 30 keV, the energy flux in the inner belt was also 10-100 times smaller than Freeman's figure. Since these three experiments were done at widely different times, one cannot exclude the possibility that the discrepancy is due to changes in the nature of the belt between 1961 and 1966.

Apparently, the only results so far reported for protons with E < 50 keV at L < 2 refer to a magnetically disturbed period; they are shown in Fig. 10 (which gives the upper limiting values; Frank, 1967b). No results for electrons with E < 50 keV have been published.

The information available on the low-energy plasma in the outer radiation belt is more detailed. During the flight of Luna 1 in January, 1959 measurements were made with charged-particle traps at distances greater than ~ $5R_e$; electron fluxes of ~ $2 \cdot 10^8$ cm^{-2} · sec^{-1} were found for an energy E > 200 eV; this figure exceeds by about an order of magnitude the high-energy electron flux at the maximum of the outer belt (Gringauz et al., 1960b). The subsequent analysis showed that these fluxes were partly recorded in the morning section of the magnetosphere inside the outer belt.

Freeman et al. (1963) recalled that with Explorer 22 it sometimes happened that low-energy electrons were observed in the daytime sector with maximum fluxes at R ~ $7R_e$; in the majority of cases, however, such electrons were not detected. The authors did not elaborate further on these observations.

On several transits of Élektron 2 across the outer belt, the charged-particle traps recorded considerable electron fluxes (up to $3 \cdot 10^8$ cm^{-2} · sec^{-1}) in the energy range 100 eV ≤ E ≤ 50 keV. On other transits, the flux was below the lower limit of the instrument, i.e., less than $2 \cdot 10^7$ cm^{-2} · sec^{-1} (Bezrukikh et al., 1965; Gringauz et al., 1966). In both cases, the trapped electrons in the outer belt with E > 100 keV, whose measurement is described by Vernov et al. (1965) and Kuznetsov et al. (1965), had an almost constant flux (its value varied by about ±10%). This led the authors to conclude that there is a soft electron component in the outer radiation belt, distinguished from the energetic trapped radiation by its greater variability.

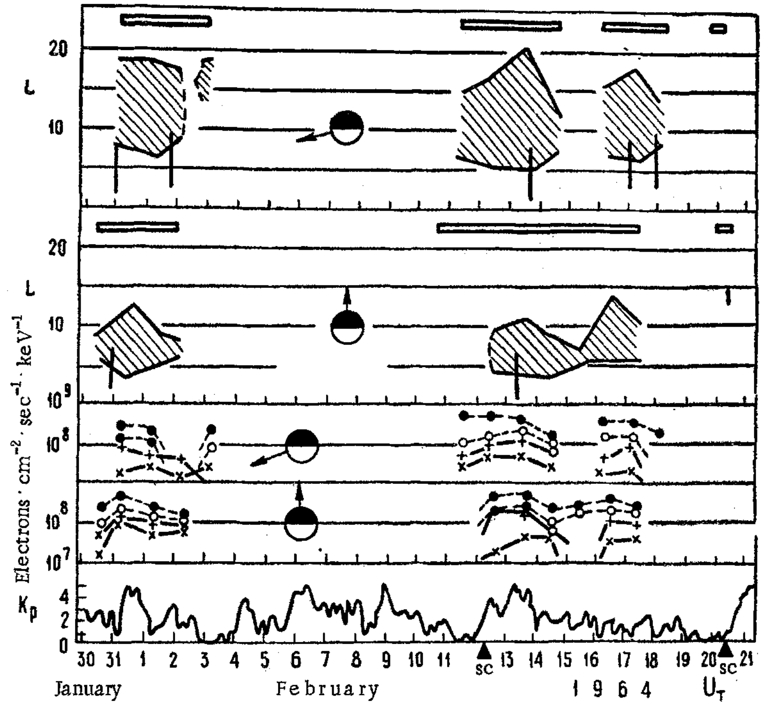

Fig. 11. Regions of enhanced low-energy electron intensity in L-coordinates and the maximum flux values in various energy intervals; spherical electrostatic analyzer data from Élektron 2. The vertical lines correspond to the position of the outer belt (Vernov et al., 1965): ●●●– 1 keV; ○○○–2.5 keV; +++ – 5 keV; ××× – 10 keV; ▭ – time over which results were available; ▲sc – sudden commencement of magnetic storm.

This conclusion was confirmed by data obtained on the same satellite from an electrostatic analyzer (for typical results see Fig. 11; Vernov et al., 1966). In addition, an indication of the boundaries of the outer radiation belt was derived from the measurements of particles with E > 100 keV; it can be seen that particles with energies 0.1-10 keV are not always observed inside the belt.

Figure 12 shows for a number of passes the L-coordinates and local times at which the charged-particle traps registered the soft electron fluxes described by Bezrukikh et al. (1965) and Gringauz et al. (1966). The circles and the squares joined by the dashed lines show the value of L and T at which during any one pass the satellite recorded a flux equal to half the maximum value observed on that pass. The crosses denote the boundaries of the outer belt as defined by the sharp drop in the flux of electrons with E > 100 keV (Kuznetsov et al., 1965). When the satellite crossed the boundary of the belt, there was no change at all in the current from the charged-particle trap; the electron fluxes continued to be observed beyond the limits of the belt.

Frank (1966) has reported on observations from the Explorer-12 CdS detector of temporal changes in the intensities of low-energy electron fluxes in the outer radiation belt during magnetic storms. He concludes that at the beginning of the giant magnetic storms of October 1 and 29, 1961, the electron energy flux in the range 100 eV < E < 40 keV increased sharply at L = 2.8-4, reaching a maximum value of 1000 ergs · cm^{-2} · sec^{-1}. No estimates of the increase in particle flux were made. Frank suggested that the low-energy electrons he observed form a ring current centered at L = 3, which is partly responsible for the main phase of the storms.

Also in 1966, the results were published of the Explorer-14 measurements on the flux of electrons with E = 5-10 keV (Pizella, Davis, and Williamson, 1966). The measurements were made by means of a photomultiplier fitted with a periodically changing absorber in the collimator; this enabled the pitch angles of the electrons to be measured; the recordings were made in the morning part of the magnetosphere (08-10 hours LT). High energy particles were also recorded.

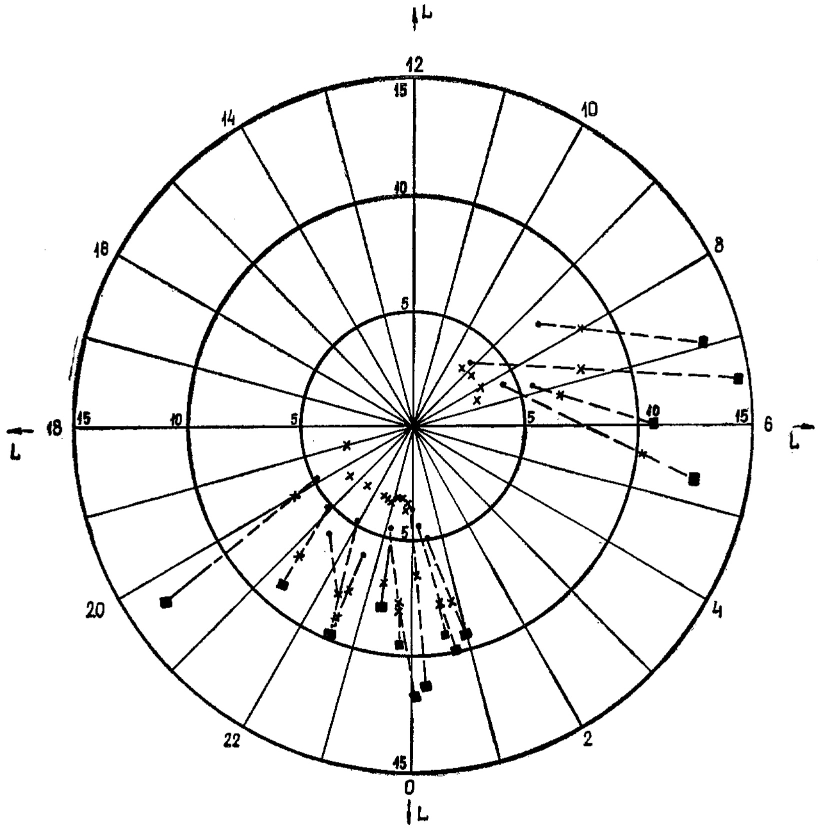

Fig. 12. Values of L-coordinate and local time for which electron fluxes with E > 100 eV were observed on Élektron 2 (details in text).

Some of the authors' conclusions are as follows. There is a region of trapped electrons having a mean energy of about 10 keV and a maximum intensity of 10^9 $cm^{-2} \cdot sec^{-1}$ at L = 8; both the value of the maximum intensity and the position change markedly with time. The electrons are trapped because they occur in the morning sector (the boundary of the magnetosphere crossed through L = 12) and because their distribution in pitch angle is typical of that for trapped particles. The authors note that the energy spectrum of these electrons is not continuous with that of the electrons at smaller L values and thus that they must not be considered as the tail of the more energetic trapped electrons, but must have some other origin and lifetime. They were not observed on all the passes of the satellite.

Pizella et al. consider these electrons to be the same as those discovered by Luna 1 on January 2, 1959 (Gringauz et al., 1960) when the inner boundary of the zone containing them corresponded to L = 5 at a geomagnetic latitude of ~ 20° and the local time was about the same as in their measurements. The authors noted the absence of any clear correlation between the electron-flux measurements and the magnetic conditions; they did not do a detailed analysis because of the limited amount of data.

It is interesting to compare the Pizella et al. results with those made on Élektron 2 for E > 100 eV. Some of the measurements in both series were made in the morning hours (see Fig. 12). In both cases, the fluxes were observed to be very variable, and sometimes they exceeded by more than an order of magnitude the high-energy electron flux in the outer belt. These common features suggest that the 5-10 keV fluxes measured by Explorer 14 in the outer belt have the same origin and properties as the fluxes recorded by Élektron 2 and Luna 1.

Measurements of the flux of charged particles with energies of hundreds and thousands of electron volts were also made on OGO-1 and OGO-3, which passed through the outer radiation belt. The MIT plasma detectors on these satellites, modulation-type charged-particle traps, could record electrons with energies from 40 eV to E ≲ 2 keV but were of comparatively low sensitivity. They did not find any electron fluxes in the evening or night sectors of the magnetosphere (Vasyliunas, 1968).

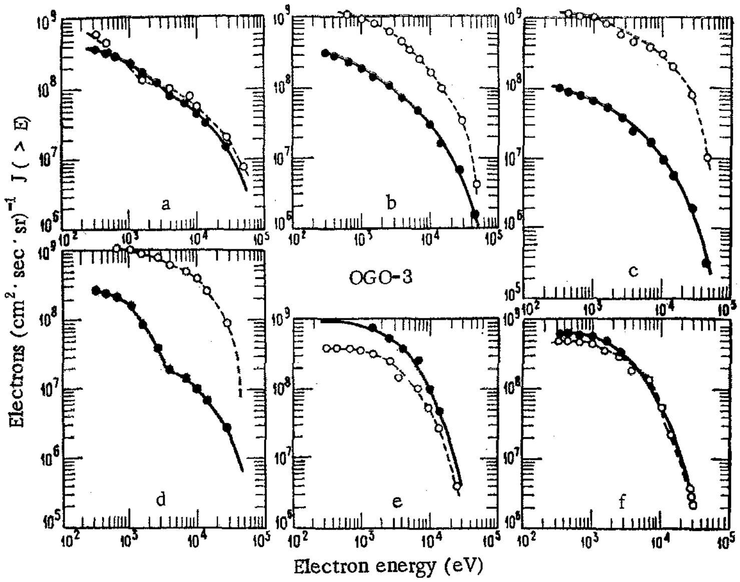

Fig. 13. Integral energy spectra of soft electrons; data from OGO-3 electrostatic analyzer (Frank, 1967b):

a) $L = 3.4$,	$\lambda = 1°$,	$\alpha = 94°$;
b) $L = 4.0$,	$\lambda = 4°$,	$\alpha = 100°$;
c) $L = 5.0$,	$\lambda = 8°$,	$\alpha = 108°$;
d) $L = 6.0$,	$\lambda = 11°$,	$\alpha = 113°$;
e) $L = 7.0$,	$\lambda = 14°$,	$\alpha = 117°$;
f) $L = 8.0$,	$\lambda = 15°$,	$\alpha = 120°$;

●●● show measurements on a magnetically quiet day; ○○○ measurements on a magnetically disturbed day.

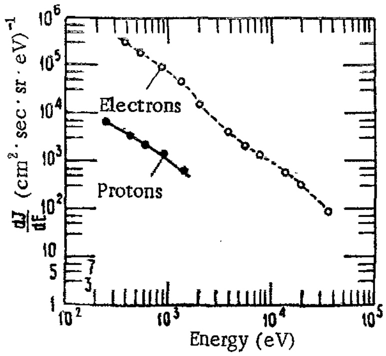

Fig. 14. Electron energy spectrum from OGO-3 electrostatic analyzer for June 15, 1966 at 0704 UT at a distance of $3.4R_e$ with L = 3.9 (Frank, 1967b).

Satellite OGO-3 was also fitted with electrostatic analyzers with energies from ~ 100 eV to ~ 50 keV and a sensitivity considerably greater than that of earlier instruments used for studying the low-energy plasma in the radiation belts (Frank, 1967b, c). Figure 13 shows the energy spectra of soft electrons in the outer belt for various magnetic shells ($3.4 \leq L \leq 8$) on June 23, 1966 (magnetically quiet day) and June 25, 1966 (severe magnetic disturbance). It can be seen that in both cases significant electron fluxes were recorded at all values of L, with maxima in the energy range from several hundred electron volts to 1 keV. The magnetic disturbance coincides with a sharp increase in the flux. Figure 14 shows one of the spectra obtained at L = 3.9 on June 15, 1966, when the flux of electrons with energies 10^3-10^4 eV was several orders of magnitude smaller than those in the previous diagram (Frank, 1967).

These data confirm the existence of a highly variable soft electron-flux component in the outer radiation belt and give the first detailed energy spectra for this component.

On OGO-3, Frank (1967c, d) also obtained the only data on the soft proton component in the outer belt. Earlier low-energy charged-particle detectors on satellites which crossed the trapped-particle region, including the electrostatic analyzers on IMP-1 (Wolfe et al., 1966a) and Élektron 2 (Vernov et al., 1966), were insufficiently sensitive to register positive ions and gave only upper limits for the ion flux. Typical results have already been shown in Fig. 10 for the flux of protons with E < 49 keV at L = 8. An example of the differential energy spectrum of these protons at L = 3.9 (together with a simultaneous electron spectrum) is given in Fig. 14. In analyzing the results of the magnetic field measurements made with Élektron 2, Dolginov et al. (1965)

concluded that there must be a ring current formed by soft protons in the outer belt; at the time, as they noted, there was no experimental evidence of such particles available.

An analysis of the considerable variations in the flux of low-energy protons and electrons in the outer radiation belt in June-July 1966 during some moderate magnetic storms led Frank (1967d) to the conclusion that the total energy of these particles during the increase phase was sufficient to cause the reduction in magnetic field observed at the surface of the earth at low and middle latitudes and that it was precisely these particles which during storms create the external ring current similar to that suggested by Chapman and Ferraro (1932). An estimate showed that the observed D_{st} disturbance of 50γ corresponded to the following total energies for particles with 200 eV $\leqslant$ E $\leqslant$ 50 keV lying between L = 1 and L = 8: $2.1 \cdot 10^{22}$ ergs for protons and $5.3 \cdot 10^{21}$ ergs for electrons. The observed lifetime τ for 30-50 keV protons during the rapid decay after the main phase of the storm was of the order of tens of hours. Swisher and Frank (1968) showed that these values of τ could be explained by a process of charge exchange between the protons and exospheric hydrogen atoms.

3. LOW-ENERGY CHARGED-PARTICLE FLUXES BEYOND THE RADIATION BELTS

In the Introduction we mentioned the first discovery of low-energy electron fluxes (E > 200 eV) beyond the radiation belts by the first moon rockets in 1959 (Gringauz et al., 1960a, b, 1961b). The intensity of these fluxes significantly exceeded (by at least an order of magnitude) the flux of electrons with E > 50 keV in the outer belt. From 1961 onwards, similar fluxes were observed by Soviet and American spacecraft, as will be described below. (We remind the reader that some data on the orbits of these craft can be found in the table in the Introduction.)

The outermost charged-particle belt, by which in 1961 was meant the intermediate zone between the earth's radiation belts and the solar wind, also includes (as has recently become clear) the transition zone on the noon side between the shock front (caused by the flow of the supersonic solar wind round the geomagnetic field) and the boundary of the magnetosphere (the magnetopause). On the night side it includes the plasma layer, which contains the neutral sheet (Gringauz and Khokhlov, 1965; O'Brien, 1967). In this survey we give a brief summary of the information on the transition zone plasma. This is because, firstly, we ourselves originally included it in the outermost charged-particle belt, and because, secondly, if the low-energy plasma flux is incident on the magnetosphere through the neutral points [as is suggested by several authors including Pletnev et al. (1965)], its source cannot be the disturbed solar wind, but rather the transformed plasma from the transition layer which bounds the magnetosphere.

The understanding of the physical nature of the low-energy charged-particle fluxes in various parts of the magnetosphere and outside it has been greatly helped by magnetic-field measurements. These, in particular, have led to some theoretically important discoveries [see, for example, Axford (1962)] about the properties of the shock wave front and the magnetospheric boundary (magnetopause) (Explorer 12, Cahill and Amazeen, 1963) and the nature of the neutral sheet in the night sector (IMP-1, Ness et al., 1964). As noted above, Fig. 1 gives the present picture of the geometry of the magnetic field round the earth.

During the many crossings of the daytime part of the magnetopause by Explorer 12 in 1961, the low-energy CdS crystal detector gave results which were interpreted as evidence of electrons with 200 eV $\leq$ E $\leq$ 40 keV and a flux of 10^9-10^{10} $cm^{-2} \cdot sec^{-1}$ in the transition layer (Freeman et al., 1963). In 1963-64 IMP-1 measured electron fluxes in the transition layer of $\sim 10^8$ $cm^{-2} \cdot sec^{-1}$ for E > 100 eV (Serbu, 1965) and of 10^8 $cm^{-2} \cdot sec^{-1}$ for 65 $\leqslant$ E $\leqslant$ 210 eV and also positive-ion spectra (Bridge et al., 1965). Similar spectra were also measured by Wolfe et al. (1966a). There have been other experiments in the transition layer, in particular, by means of positive-ion electrostatic analyzers in OGO-1 and IMP-2 (Wolfe et al., 1966a, b) and ion and electron analyzers in Vela 2 (Gosling et al., 1967).

The results obtained in the period after the launching of IMP-1 can be summarized as follows. In the transition layer there are electrons with energies E > 100 eV (Serbu, 1965) and in the range 65 $\leqslant$ E $\leqslant$ 210 eV (Bridge et al., 1965) with fluxes $\sim 10^8$ $cm^{-2} \cdot sec^{-1}$. Such electrons are not present in the undisturbed solar wind. The electron energy spectrum, as derived from the Vela data is shown in Fig. 15a (Bame et al., 1967). The proton component of the solar wind undergoes the following changes behind the shock front: the energy spectrum widens considerably; the steady velocity drops; the density increases by a factor of about 2; the temperature rises by about a factor of 5. The kinetic energy of the protons in the transition layer

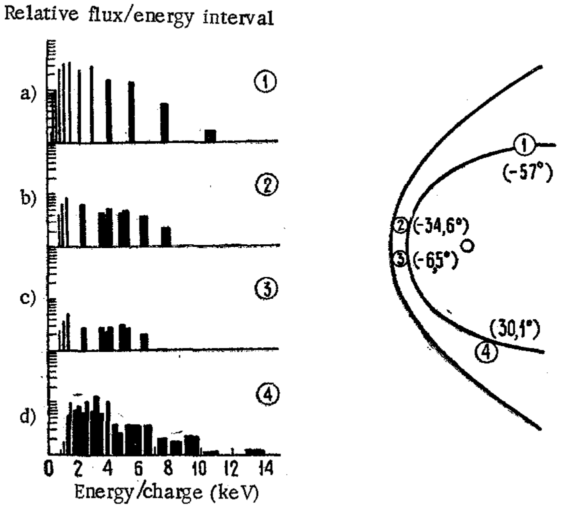

Fig. 15. Proton energy spectra measured in the transition zone by various satellites (Wolfe et al., 1966b): a) Vela 2B, October 5, 1964, 1903-1916 UT; b) IMP-2, October 5, 1964, 2029-2224 UT; c) IMP-2, October 5, 1964, 0654-0917 UT; d) OGO-1, October 4, 1964, 2010-2030 UT. On the right side of the diagram, the circled numbers correspond to the position of the satellites in the transition zone when the measurements were made.

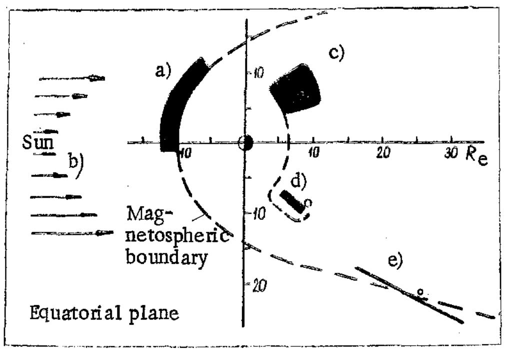

Fig. 16. Distribution of electrons with 200 eV ≤ E ≤ 40 keV in the equatorial plane (Van Allen, 1964): – – –) possible extrapolation; ——) discontinuities in the observations; OOO) measurements reduced to the plane of the geomagnetic equator along the earth—sun line. a) Freeman, 200 eV ≤ E_e ≤ 40 keV, $J_0 \sim 10^9$–10^{10} $cm^{-2} \cdot sec^{-1}$, b) Neugebauer et al., $E_p \sim 1$ keV, $J_0 \sim 10^8$ $cm^{-2} \cdot sec^{-1}$, c) Freeman, 200 eV ≤ E_e ≤ 40 keV, $J_0 \sim 10^8$–10^{10} $cm^{-2} \cdot sec^{-1}$, d) Gringauz et al., $E_e \geq 200$ eV, $J_0 \leq 2 \cdot 10^8$ $cm^{-2} \cdot sec^{-1}$, e) Bridge et al., $E_p \sim 500$ eV, $J_0 \sim 10^7$–10^8 $cm^{-2} \cdot sec^{-1}$.

is one-half that of those in the undisturbed solar wind: the loss is apparently explained by the heating of electrons and the generation of hydromagnetic waves in the transition layer (Wolfe et al., 1966). It is interesting to note that directly after the first lunar-rocket experiments (Gringauz et al., 1960; Shklovskii et al., 1960), the formation of electron fluxes with E > 200 eV beyond the trapped-radiation zone was explained in fact by the transfer of energy from the solar wind protons to the electrons as the wind hit the geomagnetic field.

The proton energy spectra obtained over a short time interval on October 4-5, 1964 in Vela 2B (Gosling et al., 1966), IMP-2, and OGO-1 (Echo) in various parts of the transition layer are shown in Fig. 15 (Wolfe et al., 1966b).

We now go on to the nighttime part of the magnetosphere. The measurements with CdS crystals on Explorer 12 confirmed the existence of a flux of 200-eV electrons beyond the outer radiation belt on the night side. The distribution of electrons with 200 eV ≤ E ≤ 40 keV in the equatorial plane of the magnetosphere is shown in Fig. 16 in the form in which it was drawn in 1964 from the Explorer-12 data (Van Allen, 1964) with a big spatial discontinuity between the day and night zones.

At the end of 1962 the charged-particle traps in the Mars-1 spacecraft recorded electron fluxes with E > 70 eV beyond the outer belt on the night side at small geocentric distances ($2R_e < R < R_e$) but at high invariant $\Lambda \sim 65$-67° (Gringauz et al., 1964; Gringauz, 1964). This experiment confirmed the original suggestion contained in the "third radiation belt" hypothesis (Gringauz et al., 1960) that the inner boundary of the soft electron fluxes is situated along the outer limit of the radiation belt, i.e., along the magnetic sheaths.

Fritz and Gurnett (1965) later reported that Injun 3 had observed 10-keV electrons beyond the outer radiation belt at the same latitudes as Mars 1. The authors consider that they were detecting the same fluxes as both Luna 1 and Mars 1.

In 1964 the Élektron-2 spherical analyzer recorded electrons with energies from 100 eV to 10 keV outside the trapped-radiation belt in the southern part of the magnetosphere at geomagnetic latitudes up to ~ 60° in the morning hours and near midnight (Vernov et al., 1965; Vernov et al., 1966). The fluxes were as high as ~ 10^9 $cm^{-2} \cdot sec^{-1} \cdot keV^{-1}$ at E = 0.2 keV and ~ $5 \cdot 10^7$ $cm^{-2} \cdot sec^{-1} \cdot keV^{-1}$ at E ~ 10 keV; it was found that the extent of the ~ 1-keV electron region was larger than that for the ~ 10-keV region. A tendency was noticed for the spectrum to become softer farther away from the earth. The size of the region and the value of the fluxes varied strongly with a characteristic time of about one day and were positively correlated with magnetic activity. Some of the areas where the Élektron-2 charged-particle traps detected electrons with E > 100 eV beyond the outer belt have already been shown in Fig. 12.

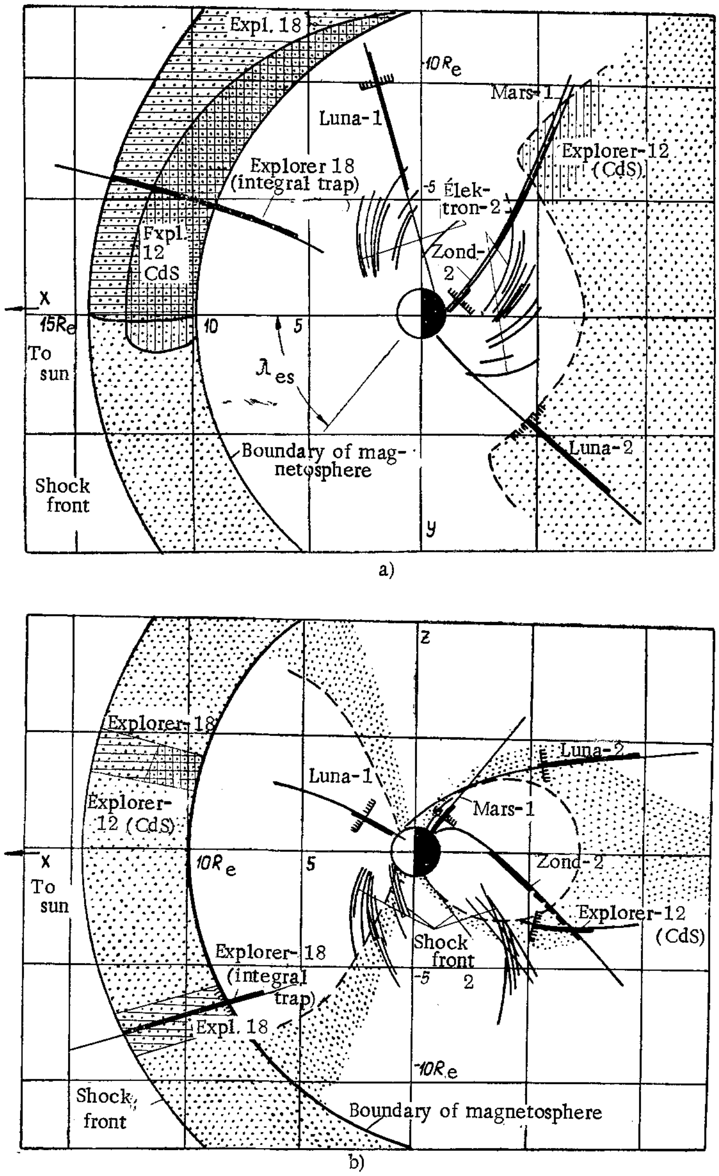

Fig. 17. Distribution of low-energy charged-particle fluxes round the earth (Gringauz and Khokhlov, 1965): a) projection onto plane of the ecliptic; b) projection onto meridian plane in solar elliptic coordinates. The parts of the spacecraft trajectories where fluxes were recorded are shown by the continuous and dashed lines; for Élektron 2 only those sections of the orbit where soft electrons were observed are shown (charged-particle trap data). The outer boundary of the outer radiation belt is shown by a thin line and a comb symbol. The suggested position of the outermost charged-particle region is shown by dots.

Figure 17 gives the distribution of low-energy charged-particle fluxes (from various satellite data), as it was seen in 1965 (Gringauz and Khokhlov, 1965). Projections are given onto (a) the plane of the ecliptic and (b) the meridian plane in a solar elliptical coordinate system. It was noted in the discussion of this diagram that there was then (1965) no proof that the day and night regions in which fluxes of electrons having energies $\leqslant 40$ keV were actually joined to form a single unit (see Fig. 17b), although the high-latitude measurements from Mars 1 and Élektron 2 (Fig. 17b) gave some reason to believe that they were in fact joined, at least at high latitudes, to produce a single region with a complicated shape.

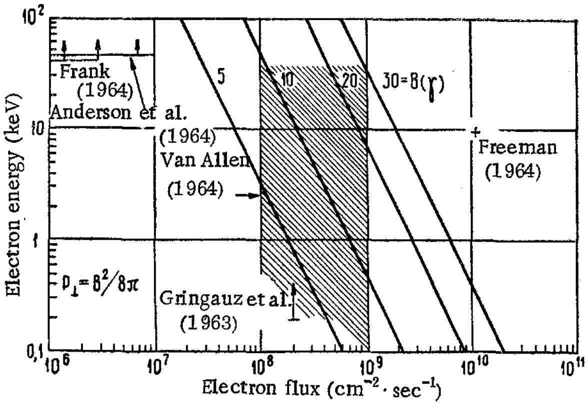

Fig. 18. Proposed pressure balance between the magnetic field in the magnetospheric tail (without allowance for the plasma) and an unmagnetized electron gas in an idealized model of the neutral sheet. The results of charged-particle observations relevant to the interpretation of the neutral sheet are shown.

On the other hand, no case had then occurred where a spacecraft with the appropriate electron detectors had crossed beyond the outer zone and not discovered low-energy electrons. Since the outer boundary of the trapped-radiation zone is closed, it was possible to suppose that the low-energy electron regions beyond it also formed a single unit. This does not mean that the plasma fluxes in the day and night parts must have a common origin and identical properties.

On the basis of these arguments, the authors of Fig. 17 found it possible to suggest that the low-energy electron fluxes in the meridian plane are situated in the region shown by the dots. We may note that, even now, the absence of measurements in the high-latitude part of the magnetosphere makes it impossible to judge the final accuracy of Fig. 17b. The Élektron-2 results led Gringauz and Khokhlov (1965) to the preliminary conclusion that there is a connection between the observed intensity of the soft electron flux and the orientation of the earth's magnetic-dipole axis relative to the direction of the sun, with maximum fluxes being observed in the morning sections of the satellite orbit when the south magnetic pole is at its greatest inclination from the sun and conditions are most favorable for the solar plasma from the transition layer to penetrate into the magnetosphere through the southern neutral point. This conclusion was confirmed by further reduction of the data by Khokhlov (1966), who also noted that there was an east–west asymmetry in the distribution of soft electrons (the fluxes are more intense and more frequent in the morning than in the evening).

Among the most important scientific results from IMP-1 is the confirmation of the fact that the magnetosphere is highly elongated in the antisolar direction. Evidence for this was also provided by the earlier magnetic measurements on Explorer 10 (Happner et al., 1963) and Explorer 12 (Cahill, 1963); and by the discovery of an essentially new phenomenon – the magnetically neutral sheet (see Fig. 1) in the nighttime magnetosphere (Ness et al., 1964; Ness, 1965).

As Axford et al. (1965) have noted, a neutral sheet in the magnetotail must be filled with a plasma flux of enhanced intensity to balance the pressure of the magnetic fields situated on either side of it and directed in opposite senses. The magnetic field of the tail (outside the neutral sheet) measured by IMP-1 was ~ 17 γ. Ness (1965) has drawn on a single diagram (Fig. 18) the results of the various authors concerning the charged-particle fluxes in the night magnetosphere which could create the plasma pressure necessary for the existence of a neutral sheet. The region where the energy and flux values satisfy the given magnetic results is shown shaded. Since our results fall in this region, Ness (1965) suggested that the Luna-2 electron flux measurements are related to the neutral sheet (an opinion also expressed by Gringauz and Khokhlov, 1965). Subsequently (1966), Pioneer 7 carried out simultaneous magnetic and plasma measurements, as the spacecraft crossed the night magnetosphere at distances of up to ~ $40R_e$, and confirmed the correctness of the idea of a quasistatic magnetotail in which the sum of the partial magnetic and plasma pressures is constant (Lazarus, Siscoe, and Ness, 1968). This experiment is discussed in slightly more detail below.

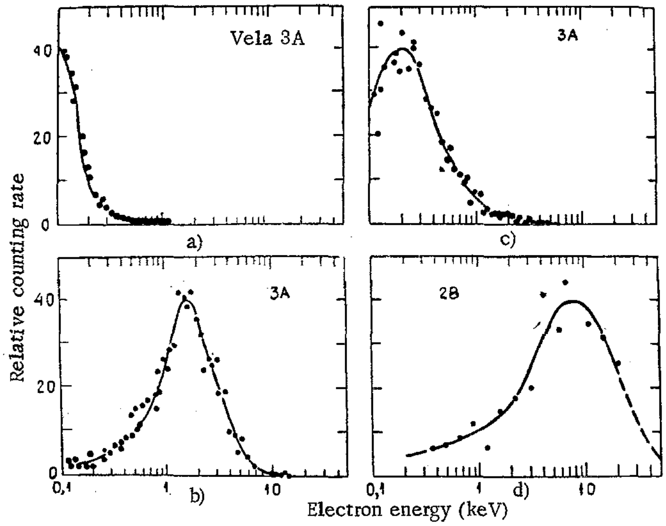

Fig. 19. Electron energy spectra measured on Vela satellite: a) in transition region (in front of shock wave); b, c, and d) in the plasma layer of the magnetotail (Bame et al., 1967).

Starting in 1964, the Vela satellites made detailed measurements of electron energy spectra in the range 350 eV $\leq$ E $\leq$ 20 keV across the magnetotail at distances of R ~ $17R_e$ (Bame et al., 1967). Examples of the spectra obtained on the spherical electron analyzers are shown in Fig. 19, b, c, and d. In addition to electrons, positive ions (mainly protons, of course) were discovered for the first time. Their flux was naturally much smaller. According to the authors' estimates, the proton and electron densities are almost equal to 1 cm^{-3}; the two energy spectra have very similar shapes. The mean electron energies were in the range 200 eV to 12 keV. The fluxes were often isotropic, though the anisotropy factor could be as high as 2.

Further detailed studies of the plasma with particle energies from ~ 200 eV to ~ 50 keV were made by means of the high-sensitivity cylindrical electron analyzers on OGO-3 in the magnetotail at $8R_e < R < 20R_e$ (Frank, 1967). (The results from this satellite referring to the radiation belts have already been discussed in Sec. 2.) These investigations complemented the Vela results. The information on the position of the plasma in the magnetospheric tail obtained from the electrostatic analyzer data on Vela and OGO-3 can be summarized as follows: the neutral sheet lies inside the plasma layer which always has the greater thickness. On Vela it was arbitrarily assumed that the boundary of the plasma layer was where the electron flux was $6 \cdot 10^7$ $cm^{-2} \cdot sec^{-1}$. With this definition, the thickness at R ~ $17R_e$ turned out to be several earth radii. On OGO-3 electron fluxes were observed at R ~ $19.5R_e$ for a distance of ~ $12R_e$ above the neutral sheet (for a given measurement half-way between the neutral sheet and the northern boundary of the magnetosphere).

Anderson (1965) and Frank (1965) reported satellite observations in the tail of sporadically appearing and disappearing "islands" of electrons with E > 45 keV. Bame et al. (1967) and Frank (1967a) consider these to belong to the tails of the spectra of low-energy plasma-layer electrons and suggest that their appearance and disappearance are explained by a rapid heating (increase in mean energy) of the electrons in this layer and a sudden cooling, i.e., rapid changes in the energy spectrum. Frank (1967a) also notes rapid spatial and temporal variations in the electron fluxes. The energy density near the "peaks" does not decrease with R (R > $13R_e$) and is almost always as high as 10^{-9} erg $\cdot$ cm^{-3}, despite the fact that the average energies decrease with R [as was noted by Vernov et al. (1966) from Élektron-2 data].

The displacement of the energy peaks toward higher values at smaller R, accompanied by the broadening of the spectrum, gives grounds for believing that an electron acceleration process is effective, at least in the tail region from ~ 10 to $20R_e$. Since the peak shifts by several kiloelectron volts at a distance of ~ $10R_e$, this can be ascribed to an electric field of ~ $5000V/10R_e \simeq 100$ mV $\cdot$ km^{-1} (Frank, 1967a).

The value quoted above for the energy density is evidence that the electrons seriously affect the magnetic field at R > $8R_e$.

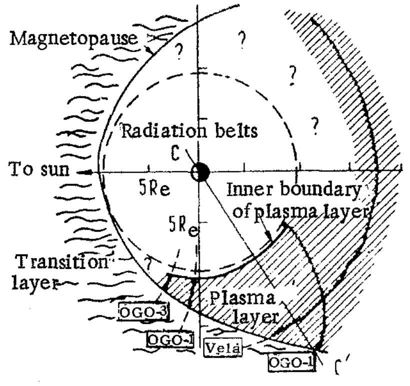

Fig. 20. Position of the region (shaded) of enhanced intensity of low-energy electrons ($E \leq 1.7$ keV) in the plane of the geomagnetic equator (Vasyliunas, 1968).

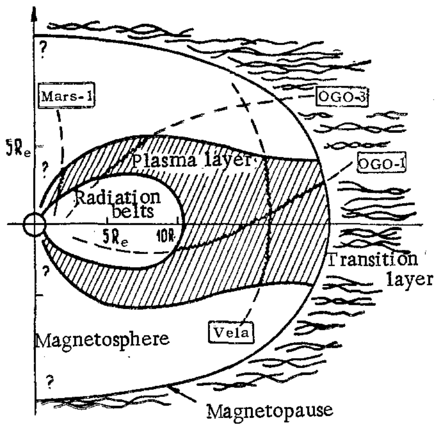

Fig. 21. The same as Fig. 20 for meridian section along the line CC' of (Vasyliunas, 1968).

In the simultaneous plasma and magnetic measurements on Pioneer 7 (Lazarus, Siscoe, and Ness, 1968), only electrons with $E \leq 1.6$ keV were recorded in the tail. It can be seen from Frank's results (1967a) that for R close to $8R_e$ the Pioneer detectors could only observe the lowest energy electrons; an accurate determination of the plasma pressure is therefore difficult. Nevertheless, the simultaneous measurements are impressive and do provide evidence for the quasistatic model of the magnetotail in which the sum of the magnetic and particle partial pressures is constant and equal to the total (dynamic, thermal, and magnetic) pressure of the surrounding solar plasma, normal to the surface of the magnetosphere. Additonal support for this model is provided in particular by the simultaneous sharp decrease in magnetic pressure and increase in plasma pressure which were observed when Pioneer 7 entered the plasma layer and the reverse changes noted on exit, and also by the phenomena recorded on entering the neutral sheet (particle density remained almost constant, but average particle velocity increased significantly).

Bame et al. (1967) suggested that the plasma layer in the magnetotail begins at the night boundary of the trapped-radiation region and that its orientation at first coincides with the equatorial plane and then, farther from the earth, with the direction of the solar wind. This is, in fact, how it is shown in Fig. 1 (Ness, 1967). The other measurements do not contradict this picture, and Vasyliunas' results (1968b) obtained from OGO-1 and OGO-3 directly confirm it. These results were obtained by means of the MIT detectors which could record the lowest energy electrons in the plasma layer ($100 \text{ eV} \leq E \leq 1650 \text{ eV}$). Figure 20 shows the distribution of low-energy electrons in the equatorial plane as given by the Vela and OGO data. Coinciding with the outer limit of the low-energy region is the boundary of the magnetosphere (defined by the existence of significant positive-ion fluxes); on the inner side there is a clear boundary close to (and possibly coincident with) the edge of the trapped-radiation zone. The analogous distribution in the meridian section, corresponding to late evening, (line CC' on Fig. 20) is shown in Fig. 21. The high-latitude details have been taken from the Mars-1 results.

The observations described by Vasyliunas show that the flux of low-energy particles just beyond the limit of the outer radiation belt is not a characteristic of the nighttime magnetosphere alone, but also always occurs in the evening and possibly the daytime sections. It will be very interesting to see the Vasyliunas data for the daytime sector. These results strongly support the idea of an outermost charged-particle belt surrounding the radiation belts on all sides, as was proposed earlier by us (Gringauz, 1961a, 1964; Gringauz and Khokhlov, 1965). It is, however, somewhat unexpected to find such a definite inner boundary to the observed electron fluxes, which cease quite sharply near the limit of the outer belt. This sharp boundary was not observed on other spacecraft (see, for example, Figs. 12 and 17 for the charged-particle trap recordings of electrons with $E > 100$ eV on Élektron 2). It seems also that Frank did not detect it on OGO-3, or at least he did not mention it in his papers (1967a, b). It is possible that it is a characteristic only of those low-energy electrons ($E < 1.6$ keV) whose distribution is shown in Figs. 19 and 20.

During bay-type magnetic storms, there is a movement of the inner boundary of the soft electron region toward the earth (Vasyliunas, 1968), as shown in Fig. 22. The author has noted the possible connection between this and the corresponding movement of ion fluxes reported earlier by Freeman and Maguire (1967).

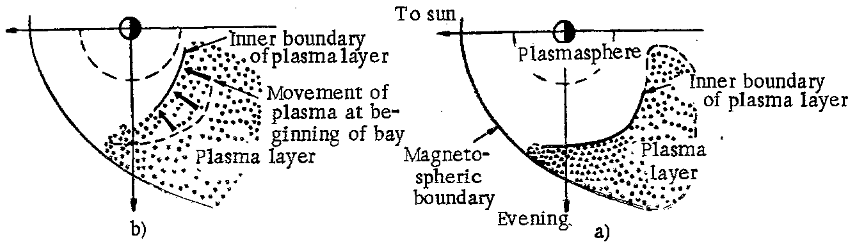

Fig. 22. Schematic distribution of low-energy electrons (E ≤ 1.7 keV) in the evening sector of the equatorial plane of the magnetosphere (Vasyliunas, 1968): a) magnetically quiet period; b) magnetically disturbed period.

To conclude this part of the survey, we will mention some plasma measurements made in other parts of the tail. The existence of the tail at distances $R < 31R_e$ was proved by the IMP-1 results (Ness et al., 1964). As regards plasma properties, the magnetotail differs from the undisturbed interplanetary space and the transition layer behind the shock front in the sharp decrease in proton flux. This criterion was used to define the tail with the first lunar satellite Luna 10, which was launched in March 1966; the results showed that in each month the moon takes four days to cross the magnetotail, i.e., the length of the tail is not less than $\sim 80R_e$ (Gringauz et al., 1966). Inside the tail, electron fluxes $\sim 10^8$ $cm^{-2} \cdot sec^{-1}$ were observed for electrons with E > 70 eV (apparently the plasma layer).

Also in 1966, magnetic measurements on the earth satellite Explorer 33 showed that the length of the magnetotail was not less than 510,000 km; they thus confirmed the Luna-10 result that the moon passes through the tail (Ness et al., 1967; Ness, 1967).

Of very great interest are the plasma and magnetic measurements made on Pioneer 7 at a distance of $\sim 1000R_e$. At the moment, only preliminary results are available. In contrast to the plasma measurements in the tail made with IMP-1 (Wolfe et al., 1966c) and Luna 10 (Gringauz et al., 1966), the electrostatic analyzer data from Pioneer 7 for the region around the earth–sun line did not show a sharp fall in the solar plasma ion flux, but did indicate a marked distortion in the shape of the ion energy spectra (Wolfe et al., 1967). The authors believe that either Pioneer 7 was in a turbulent zone beyond the magnetosphere or that at these large distances the solar wind diffuses inside the tail.

Ness et al. (1967) described simultaneous magnetic measurements which also showed a difference between the observed field and the undisturbed interplanetary field, but in their opinion it is not yet possible to draw any final conclusion about the nature of these differences. Fairfield (1968), in comparing the simultaneous field measurements in Pioneer 7 at $\sim 1000R_e$ and in Explorers 33 and 35 in the interplanetary space around the earth, came to the conclusion that Pioneer 7 was observing oscillations in the magnetotail. It seems to us, however, that a final solution of this question requires further comparisons between the two sets of measurements on this satellite.

CONCLUSIONS

The study of the low-energy plasma in various parts of the magnetosphere shows that its properties (particularly, its distribution) vary with geomagnetic disturbance. This is true both of the plasma in the outer ionosphere, which is apparently rotating with the earth, and of the plasma above the plasmapause.

Nobody now doubts that a geomagnetic disturbance represents changes in some property (or properties) of the solar wind, although the various authors have different opinions on the details. Some of the properties which have been suggested as determining the K_p index are the velocity (Snyder et al., 1963), the direction of the interplanetary field (Dessler and Walters, 1964), the direction of the plasma velocity (Coleman, 1967), and so on. Whichever of these authors is closest to the truth, it is quite clear that the position of the plasmapause and of the boundary of the trapped-radiation zone, the distribution and properties of the magnetospheric plasma with 100 eV < E < 50 keV, and the auroras and magnetic storms caused by the particles in this plasma are all ultimately connected with processes arising in the interplanetary medium. Measurements made simultaneously inside and outside the magnetosphere have so far only led to some rough empirical relationships, such as that between the speed of the solar wind and K_p (Snider et al., 1963) or between the electric field in the evening meridian plane and the solar wind velocity (Vasyliunas, 1968a).

There is every reason to hope that in the near future experiments will make it possible to choose the correct idea from the wealth of available hypotheses on the connections between the processes inside and outside the magnetosphere, or if necessary, to create a new theory. The results of further measurements on the low-energy plasma would seem, together with magnetic-field measurements, to be fundamental to this purpose.

We would like to indicate some important still-unsolved tasks in the experimental study of the low-energy plasma and some related problems which have not been discussed (or have been inadequately discussed) in this survey.

1. Despite the considerable progress achieved (especially by the OGO satellites) in recent years in the study of the low-energy plasmas – both the thermal type and that with energies from hundreds of electron volts to tens of kiloelectron volts – work on the mapping of the flux distribution in the magnetosphere and its variations is still far from being completed. In the region $R > 2R_e$ at geomagnetic latitudes $\varphi_m > 45°$, the only measurements so far are those of Mars 1 and the Élektron satellites. This region, which is intermediate between the intensively studied part of the magnetosphere with $\varphi_m < 45°$ and the area in which auroras and other similar phenomena occur, and which is characterized by high latitudes but low heights, most certainly requires further investigation.

2. As pointed out in the previous section, the data obtained from Élektron 2 are evidence of a relation between the observed soft electron fluxes and the angle of inclination of the dipole field and support the hypothesis that the solar wind penetrates from the transition layer into the magnetosphere through the neutral points of the magnetopause. In order to prove this, it would be very useful to have direct measurements of the value and direction of the low-energy plasma fluxes in the immediate neighborhood of the neutral points; this requires satellites with suitable orbits.

3. It is not yet clear what is the source of the low-energy plasma which takes part in the convective motion in the magnetosphere – whether it is the terrestrial ionosphere or the solar plasma penetrating through the open tail or the magnetopause. It seems that the plasma would be much colder in the first case than in the second. It is therefore very important to work out a reliable method of measuring a plasma temperature of the order of fractions or units of an electron volt at concentrations of 10^2 cm^{-3} (in the outer ionosphere) or 1 cm^{-3} (above the plasmapause).

4. In this survey there has not been space for the problem of magnetospheric electric fields [although they were mentioned in connection with the discovery of plasma convection by ATS-1 and the hardening of the spectra at the edge of the outer belt (OGO-3, Élektron 2)]. The action of an electric field can explain the movement of electrons with $E \lesssim 2$ keV during a magnetic storm (see Fig. 22). The survey by Obayashi and Nishida (1968) is specifically devoted to large-scale electric fields in the magnetosphere.

There is no doubt that the movement of charged particles in the magnetosphere (especially low-energy ones) is determined largely by electric fields. Therefore, direct measurements of such fields must definitely be included in any future program of low-energy plasma studies.

The author considers it his pleasant duty to thank V. V. Bezrukikh and É. K. Solomatina for their help in the preparation of this survey.

LITERATURE CITED

1. R. A. Anderson, J. Geophys. Res., 70, 4741, 1965.
2. J. J. Angerami and D. L. Carpenter, J. Geophys. Res., 71, 711, 1966.
3. W. I. Axford and C. O. Hines, Canadian J. Physics, 39, no. 10, 1397, 1961.
4. W. I. Axford, J. Geophys. Res., 67, 3791, 1962.
5. W. I. Axford, E. E. Petschek, and J. L. Siscoe, J. Geophys. Res., 70, 1231, 1965.
6. W. I. Axford, J. Geophys. Res., 73, 6855, 1968.
7. P. Bauer, Preprint: The Cooling of the Photonosphere, Scientific Report, University of Michigan, 1967.
8. S. J. Bame, J. R. Asbridge, H. F. Felthauser, E. W. Hones, and I. B. Strong, J. Geophys. Res., 72, 113, 1967.

9. P. M. Banks and F. E. Holzer, Preprint: The Polar Wind Report of Institute for Pure and Applied Physical Sciences, JPAPS-67/68-213, 1968.
10. V. V. Bezrukikh and K. I. Gringauz, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 177, 1965.
11. V. V. Bezrukikh, K. I. Gringauz, L. S. Musatov, and É. K. Solomatina, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 418, 1965.
12. V. V. Bezrukikh, K. I. Gringauz, M. Z. Khokhlov, L. S. Musatov, and R. Ye. Rybchinsky, Space Res., 6, 862, 1966.
13. V. V. Bezrukikh, T. K. Breus, and K. I. Gringauz, Kosmicheskie issledovaniya, 5, 798, 1967.
14. V. V. Bezrukikh, Report to the Symposium on the Physics of the Magnetosphere, Washington, [in Russian], 1968.
15. J. H. Binzack, J. Geophys. Res., 72, 5231, 1967.
16. J. L. Block, J. Geophys. Res., 71, 885, 1966.
17. L. H. Brace and B. M. Reddy, J. Geophys. Res., 70, 5783, 1965.
18. H. S. Brice, J. Geophys. Res., 72, 5193, 1967.
19. H. S. Bridge, A. Egidi, A. Lazarus, and E. Lyon, Space Research, 5, 969, 1965.
20. J. A. Van Allen, Report to the Fifth IGY Assembly, Moscow, 1958.
21. J. A. Van Allen, J. Geophys. Res., 69, 1011, 1964.
22. V. M. Vasyliunas, J. Geophys. Res., 73, 2529, 1968a.
23. V. M. Vasyliunas, J. Geophys. Res., 73, 2339, 1968b.
24. S. N. Vernov and A. E. Chudakov, Report to the Fifth IGY Assembly, Moscow [in Russian], 1958.
25. S. N. Vernov, A. E. Chudakov, P. V. Vakulov, E. V. Gorchakov, S. N. Kuznetsov, Yu. I. Logachev, A. G. Nikolaev, É. N. Sosnovets, I. A. Rubinshtein, V. G. Stolpovskii, and V. A. Él'tekov, Studies of Cosmic Space [in Russian], Nauka, Moscow, 394, 1965.
26. S. N. Vernov, V. V. Mel'nikov, I. A. Savenko, B. I. Savin, and T. I. Pervaya, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 381, 1965.
27. S. N. Vernov, V. V. Melnikov, I. A. Savenko, and B. I. Savin, Space Res., 6, 746, 1966.
28. J. H. Wolfe, R. W. Silva, and M. A. Myers, J. Geophys. Res., 71, 1319, 1966a.
29. J. H. Wolfe, R. W. Silva, and M. A. Myers, Space Res., 6, 680, 1966b.
30. J. H. Wolfe, R. W. Silva, D. D. McKibbin, and R. H. Mason, J. Geophys. Res., 72, 4577, 1967.
31. J. S. Geisler and S. A. Bowhill, J. Atmos. Terr. Phys., 27, 457, 1119, 1965.
32. J. E. C. Gliddon, Aeronomy Report no. 12, University of Illinois, 1966.
33. J. T. Gosling, J. R. Asbridge, S. I. Bame, and I. B. Strong, Trans. Amer. Geophys. Union, 47, 141, 1962.
34. J. T. Gosling, J. R. Asbridge, S. I. Bame, and I. B. Strong, J. Geophys. Res., 72, 101, 1967.
35. K. I. Gringauz, V. V. Bezrukikh, V. D. Ozerov, and R. E. Rybchinskii, DAN SSSR, 131, 1301, 1960.
36. K. I. Gringauz, V. G. Kurt, V. I. Moroz, and I. S. Shklovskii, Astron. zh., 37, 716, 1960.
37. K. I. Gringauz, Space Research, 2, 539, 1961a.
38. K. I. Gringauz, Space Research, 2, 574, 1961b.
39. K. I. Gringauz, S. M. Balandina, T. A. Bordovsky, and N. M. Shutte, Space Research, 3, 432, 1963.
40. K. I. Gringauz, V. V. Bezrukikh, L. S. Musatov, and R. Ye. Rybchinsky, Space Research, 4, 621, 1964.
41. K. I. Gringauz, J. Geophys. Res., 69, 1007, 1964.
42. K. I. Gringauz and M. Z. Khokhlov, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 467, 1965.
43. K. I. Gringauz, V. V. Bezrukikh, M. Z. Khokhlov, G. N. Zastenker, A. P. Remizov, and L. S. Musatov, Kosmicheskie issledovaniya, 4, 857, 1966.
44. K. I. Gringauz, V. V. Bezrukikh, L. S. Musatov, R. Ye. Rybchinsky, and E. K. Solomatina, Space Res., 6, 850, 1966.
45. K. I. Gringauz, in: Solar-Terrestrial Physics, ed. J. W. King and W. S. Newman, Academic Press, 341, 1967.
46. E. L. Hagg, Canadian J. Phys., 45, 27, 1967.
47. J. P. Happner, N. F. Ness, C. S. Scearce, and T. L. Skillman, J. Geophys. Res., 68, 1, 1963.
48. A. J. Dessler and R. D. Juday, Planetary and Space Science, 13, no. 1, 63, 1965.
49. A. J. Dessler and G. K. Walters, Plan. Space Science, 12, 227, 1964.
50. A. J. Dessler and F. C. Michel, J. Geophys. Res., 71, 1421, 1966.
51. Sh. Sh. Dolginov, E. G. Eroshenko, and A. N. Zhuzgov, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 342, 1965.

52. J. W. Dungey, Phys. Rev. Lett., 6, 47, 1961.
53. J. W. Dungey, J. Geophys. Res., 70, 1735, 1965.
54. J. W. Dungey, Solar-Terrestrial Physics [Russian translation], ed. I. A. Zhilin and G. A. Skuridin, izd. Mir, Moscow, 153, 1968.
55. L. D. Kavanagh, J. W. Freeman, and A. J. Chen, J. Geophys. Res., 73, 5511, 1968.
56. L. J. Cahill and P. G. Amazeen, J. Geophys. Res., 68, 1835, 1963.
57. L. J. Cahill, Trans. Amer. Geophys. Union, 45, 231, 1964.
58. D. L. Carpenter, Report to 14th General Assembly of URSI, Tokyo, 1963.
59. D. L. Carpenter and R. L. Smith, Reviews of Geophys., 2, 415, 1964.
60. D. L. Carpenter, J. Geophys. Res., 71, 693, 1966.
61. D. L. Carpenter, C. J. Park, and M. J. Taylor, Trans. Amer. Geophys. Union, 49, 254, 1968.
62. S. Chapman and V. C. A. Ferraro, Terrestrial Magn. and Atm. Electr., 37, 147, 421, 1932.
63. P. J. Coleman, J. Geophys. Res., 72, 5518, 1967.
64. S. N. Kuznetsov, É. N. Sosnovets, and V. G. Stolpovskii, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 420, 1965.
65. A. J. Lazarus, G. L. Siscoe, and N. F. Ness, J. Geophys. Res., 73, 2399, 1968.
66. C. E. Mc Ilwain, J. Geophys. Res., 66, 3681, 1961.
67. N. F. Ness, C. S. Scearce, and J. B. Seak, J. Geophys. Res., 69, 3531, 1964.
68. N. F. Ness, J. Geophys. Res., 70, 2989, 1965.
69. N. F. Ness, Solar-Terrestrial Physics [Russian translation], ed. I. A. Zhulin and G. A. Skuridin, izd. Mir, Moscow, 115, 1968.
70. N. F. Ness, K. W. Behannon, S. C. Cantarano, and C. S. Scearce, J. Geophys. Res., 72, 927, 1967.
71. N. F. Ness, C. S. Scearce, and S. C. Cantarano, J. Geophys. Res., 72, 3769, 1968.
72. A. Nishida, J. Geophys. Res., 71, 5669, 1966.
73. T. Obayashi, The Report on Ionosphere and Space Res. in Japan, 28, 3, 228, 1964.
74. T. Obayashi and A. Nishida, Space Science Rev., 8, 3, 1968.
75. J. O'Brien, J. Geophys. Res., 68, 989, 1963.
76. J. O'Brien, Preprint: Relation of Auroral Radiation to the Magnetopause and to Van Allen Radiation, Department of Space Science, Rice University, Houston, Texas, 1966.
77. J. O'Brien, Solar-Terrestrial Physics [Russian translation], ed. I. A. Zhulin and G. A. Skuridin, izd. Mir, Moscow, 243, 1968.
78. I. Pizzella, L. P. Davis, and J. W. Williamson, J. Geophys. Res., 71, 5495, 1966.
79. V. D. Pletnev, G. A. Skuridin, V. P. Shalimov, and P. N. Shvachunov, Studies of Cosmic Space [in Russian], izd. Nauka, Moscow, 285, 1965.
80. J. G. Roederer, Conjugate Point Phenomena, Preprint of the paper presented to IQSY/COSPAR Symposium, London, 1967.
81. M. V. Samokhin, Geomagnetizm i aéronomiya, 6, 983, 1966.
82. M. V. Samokhin, Geomagnetizm i aéronomiya, 7, 411, 1967a.
83. M. V. Samokhin, Kosmicheskie issledovaniya, 5, 378, 1967b.
84. M. V. Samokhin, Report to Symposium on Physics of the Magnetosphere, Washington [in Russian], 1968.
85. G. P. Serbu, Space Research, 4, 564, 1965.
86. G. P. Serbu and E. J. R. Maier, J. Geophys. Res., 71, 3755, 1966.
87. G. P. Serbu and E. J. R. Maier, Space Res., 7, 527, 1967.
88. C. W. Snyder, M. Neugebauer, and U. R. Rao, J. Geophys. Res., 68, 6361, 1963.
89. R. L. Swisher and L. A. Frank, J. Geophys. Res., 73, 5665, 1968.
90. H. A. Taylor, H. C. Brinton, and C. R. Smith, J. Geophys. Res., 70, 5769, 1965.
91. H. A. Taylor, H. C. Brinton, and M. W. Pharo, J. Geophys. Res., 73, 961, 1968.
92. J. O. Thomas and A. Y. Sader, J. Geophys. Res., 69, 4561, 1964.
93. D. H. Fairfield, J. Geophys. Res., 73, 6179, 1968.
94. L. A. Frank, J. Geophys. Res., 70, 1593, 1965.
95. L. A. Frank, J. Geophys. Res., 71, 4631, 1966.
96. L. A. Frank, J. Geophys. Res., 72, 185, 1967a.
97. L. A. Frank, J. Geophys. Res., 72, 1905, 1967b.
98. L. A. Frank, On the Distribution of Low Energy Protons and Electrons in the Earth's Magnetosphere, Preprint, Department of Physics and Astronomy, The University of Iowa, 1967c.
99. L. A. Frank, J. Geophys. Res., 72, 3753, 1967d.

100. L. A. Frank and R. L. Swisher, J. Geophys. Res., 73, 442, 1968.
101. J. W. Freeman, J. Geophys. Res., 67, 921, 1962.
102. J. W. Freeman, J. A. Van Allen, and L. J. Cahill, J. Geophys. Res., 68, 2121, 1963.
103. J. W. Freeman, J. Geophys. Res., 69, 1691, 1964.
104. J. W. Freeman, J. Geophys. Res., 73, 4151, 1968.
105. J. W. Freeman and J. J. Maguire, Preprint, Particle Dynamics at the Synchronous Orbit, Department of Space Science, Rice University, Houston, Texas, 1967.
106. J. W. Freeman, C. S. Warren, and J. J. Maguire, J. Geophys. Res., 73, 5719, 1968.
107. J. W. Freeman and D. T. Young, Trans. Amer. Geophys. Union, 49, 227, 1968.
108. L. A. Fritz and D. A. Gurnett, J. Geophys. Res., 70, 2485, 1965.
109. M. Z. Khokhlov, Abstracts of Report to the Belgrade Symposium on Solar-Terrestrial Physics [in Russian], 1966.
110. I. S. Shklovskii, V. I. Moroz, and V. G. Kurt, Astron. zh., 37, 931, 1960.