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Low-Energy Plasma in the Earth's Magnetosphere[1]

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Abstract. The low-energy plasma fluxes in the earth's magnetosphere, with energies from thermal up to ~50 kev, are an important factor in determining many of the essential properties of the magnetosphere. Currents produced by the motion of these charged particles play a key role in the development of magnetic storms and in the production of auroras and the geomagnetic tail. This paper will review the experimental observations of this plasma obtained over the last decade in different regions of the magnetosphere, considered in order of increasing distance from the earth. The similarity of results from measurements of the ion and electron components of the earth's thermal plasma envelope and the dependence of the altitude of the boundary of this envelope (the 'plasmapause') on geomagnetic activity are described. Within the radiation belts there exists a low-energy plasma component that is much more variable than the energetic component; the variation of low-energy plasma fluxes in the outer belt seems to be the main cause of geomagnetic storms. The radiation belts are always surrounded by low-energy plasma fluxes; on the night side these fluxes become a part of the thick plasma layer within which is imbedded the neutral sheet of the geomagnetic tail. Experimental data on low-energy plasma at geocentric distances $>2\ R_E$ and geomagnetic latitudes $>45°$ are very scarce; this region needs intensive investigation.

1. INTRODUCTION

Experiments conducted over the last decade by means of artificial earth satellites and other space vehicles have brought about drastic changes in the concepts of the physical properties of circumterrestrial space which had been formed earlier on the basis of ground observations. In particular, the dimensions of the earth's plasma envelope (i.e., the ionosphere, consisting of charged particles of very low (thermal) energies) have turned out to be much larger than was supposed, the earth's radiation belts have been discovered, and the configuration of the geomagnetic field at considerable distances from the earth toward the sun has been found to differ essentially from the dipole field and in the antisolar direction loses any resemblance to it, forming a magnetic tail hundreds of earth radii in length.

All these newly found phenomena are very closely associated with geomagnetic disturbances caused by the interaction of the geomagnetic field with the solar wind. As a result of this interaction near the earth, charged particle fluxes having different velocities, from thermal to relativistic, appear and are

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distributed in a complicated way. The spatial distribution of these fluxes is largely determined by the structure of the magnetic field near the earth and, in turn, strongly affects the structure of this field, especially at geocentric distances exceeding 7–10 R_E.

The altitude of the zone of a sharp decrease of charged particle density in the earth's cold plasma envelope detected in 1959 at distances R of about 4 R_E [*Gringauz et al.,* 1960*a*; *Gringauz,* 1961*a*] has proved strongly dependent on geomagnetic activity [*Carpenter,* 1963*b*, 1966].

After the discovery of definitely shaped radiation belts in 1958 during experiments aimed at studying cosmic rays [*Van Allen,* 1958; *Vernov and Chudakov,* 1958], the first impression was that the outer boundary of the radiation belts, corresponding to R of about 7–8 R_E, was the outer boundary of near-earth space. The trapped radiation zone was then supposed to be symmetrical with respect to the geomagnetic dipole, the dependence of its characteristics on local time being detected only at the end of 1961 [*O'Brien,* 1963].

In 1959, during the flights of the Soviet Luna vehicle and as a result of experiments aimed at investigating the interplanetary plasma, it was discovered that beyond the boundary of the outer radiation belt there were zones having significant fluxes of low-energy electrons ($E >$ 200 ev) not recorded by cosmic ray counters. It was natural to assume that outside the boundary of the outer radiation belt there was a third radiation belt consisting of soft electrons and resembling the outer belt in shape, but characterized by larger fluxes of electrons of lower energies [*Gringauz et al.,* 1960*a, b*]. In 1961 the zone of these fluxes was called the outermost belt of charged particles [*Gringauz,* 1961*a*]. At that time, the dependence of the characteristics of fluxes in this zone on local time was not known.

At present we know that fluxes of low-energy electrons beyond the boundary of the outer radiation belt in the noon direction belong to the unstable radiation zone (reaching the magnetosphere boundary) and to partially thermalized solar plasma formed behind the front of a shock wave that appears during the interaction of the supersonic flow of the solar plasma (solar wind) with the geomagnetic field. Fluxes of low-energy electrons beyond the radiation belt boundary on the midnight side are observed in the unstable radiation zone and in the plasma layer in the magnetospheric tail, inside of which there is a magnetically neutral layer. However, when these electron fluxes were detected for the first time, nothing was known about the degree of difference of the geomagnetic field structure outside the radiation belts (i.e., at geocentric distances of more than 7–10 R_E) on the earth's day and night sides.

Modern concepts of the structure of the earth's magnetosphere are reflected in Figure 1, which shows one of the latest diagrams of the magnetosphere [*Ness,* 1967].

In the present paper references will be made to this sketch. However, we should mention that, although it shows several zones in which charged particle fluxes exist, it does not fully describe the distribution of charged particles in the magnetosphere. Apparently, the author of the sketch had no such intention. For example, he does not show the earth's plasma envelope (ionosphere), which

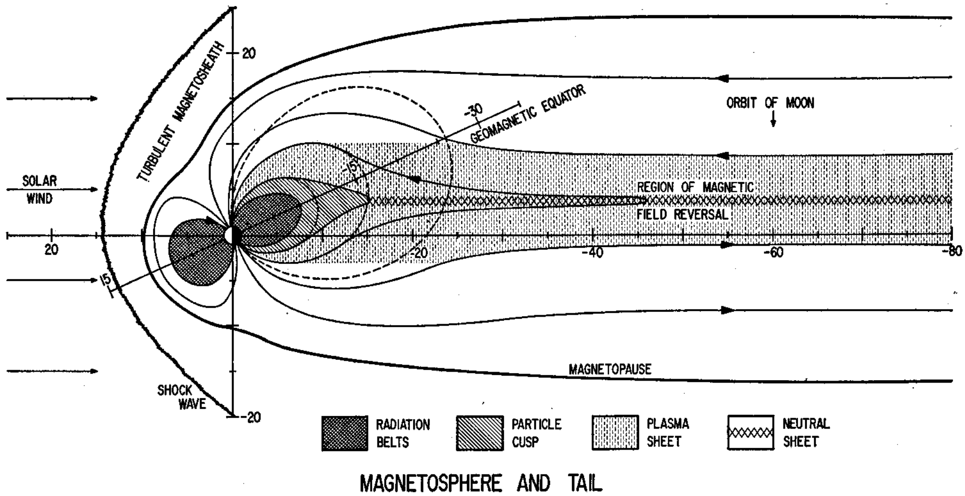

Fig. 1. Geomagnetic field structure distorted by the solar wind (magnetic meridian plane of the earth's magnetosphere) [*Ness*, 1967]

consists of particles of very low (thermal) energies and whose boundary passes inside the trapped radiation zone (more precisely, inside the outer radiation belt). On the night side of the magnetosphere the radiation belt is shown surrounded by plasma fluxes, but on the day side beyond the radiation belt boundary the plasma is not shown. Actually, plasma fluxes exist there in the unstable zone of radiation and farther in the transition layer beyond the magnetospheric boundary.

Such a stable structure of the magnetic field in circumterrestrial space, with an enormous extent in the antisolar direction as shown in Figure 1, was unexpected in the 1950's. Clearly, this structure results from a reasonably stable system of electric currents superimposed on the magnetic field of the earth's dipole. It is also evident that these currents cannot be produced by fluxes of charged particles with energies $E > 50$ kev in the radiation belts lying at relatively small distances from the earth, where the magnetic field still differs relatively little from a dipole and the kinetic energy of the particles per unit volume $\Sigma\, mv^2/2$ constitutes only a small part of the magnetic-field energy $B^2/8\pi$.

Such electric currents can, however, be produced by fluxes of charged particles with relatively low energies ($E < 30$–50 kev) which always exist outside the radiation belts. These fluxes of low-energy charged particles supply the radiation belts with particles and are of decisive importance in the creation of auroras and associated phenomena; because of this, some authors call them 'auroral radiation.' The term was introduced by *Dessler and Juday* [1965] for denoting the fluxes of low-energy plasma coming to auroral zones from the magnetospheric tail. *O'Brien* [1967*a*, *b*] complemented this concept by including charged particle fluxes on the day and night sides of the unstable radiation zone, i.e., in the region $8 < L < 10$. (See the ensuing discussion on the use of the L coordinate in this paper.)

Fluxes of low-energy charged particles also exist inside the radiation belts. Although they are extremely variable in time, their magnitude sometimes far exceeds those of much more stable fluxes of high-energy particles [*Gringauz et al.*, 1965, 1966*a*; *Pizzella et al.*, 1966] and can cause magnetic storms [*Frank*, 1967*c*].

Thus the investigation of low-energy plasma is one of the basic problems of magnetospheric physics. The main properties of the magnetosphere and the main events taking place in it are determined by the distribution of low-energy plasma in the magnetosphere and by the characteristics and behavior of this plasma (which, in turn, depend on the solar wind).

In the present review paper we consider the low-energy plasma (consisting of particles with energies ranging from thermal to ~50 kev) in different regions of the magnetosphere in order of increasing distance from the earth. The main emphasis is on description of the experimental results.

Despite their importance, investigations of low-energy plasma in the magnetosphere developed much more slowly than studies of high-energy trapped radiation. This was partly due to the difficulty of designing instruments appropriate for measuring low-energy charged particles free from such influences as the solar ultraviolet radiation and the secondary effects of hard radiation.

After the detection of low-energy plasma fluxes in the magnetosphere, studies were made by 'integral' instruments that could only indicate that the particle energies lay within the range from hundreds of ev to the minimum energies recorded by the high-energy particle counters [*Gringauz et al.*, 1960*a*, *b*, 1964; *Freeman*, 1964]. In recent years measurements with a much higher resolution of particle energies have been made [*Vernov et al.*, 1965*b*; *Frank*, 1967*a*, *b*; *Vasyliunas*, 1968*b*; etc.].

The results of the experiments on magnetospheric low-energy plasma and the state of understanding of related problems have been outlined in recent years in some review papers and in introductions to original papers [*Bezrukikh and Gringauz*, 1965; *Taylor et al.*, 1965; *Gringauz and Khokhlov*, 1965; *Carpenter and Smith*, 1964; *Carpenter*, 1966; *O'Brien*, 1967*a*; *Dungey*, 1967; *Ness*, 1967; *Binsack*, 1967; *Frank*, 1967*a*; *Vasyliunas*, 1968*b*; etc.].

In this paper we summarize the data published up to the present symposium. The limited scope of the paper prevents us from considering the problems of the techniques of measuring low-energy charged particles in outer space, although they are undoubtedly of great interest.

In this paper we use the magnetic-shell parameter L introduced by *McIlwain* [1961]. For a dipole field L equals the geocentric equatorial radius of the geomagnetic shell expressed in R_E. At high latitudes and for $L > 8$–10, this parameter has no physical sense, since the geometry of the actual geomagnetic field approximately corresponds to the picture shown in Figure 1. However, many authors when presenting experimental data continue to use this parameter even when $L > 10$. That convention will be followed in this paper.

Some characteristics of space probes and satellites that crossed the magnetosphere and were equipped with instruments for studying plasma are listed in Table 1.

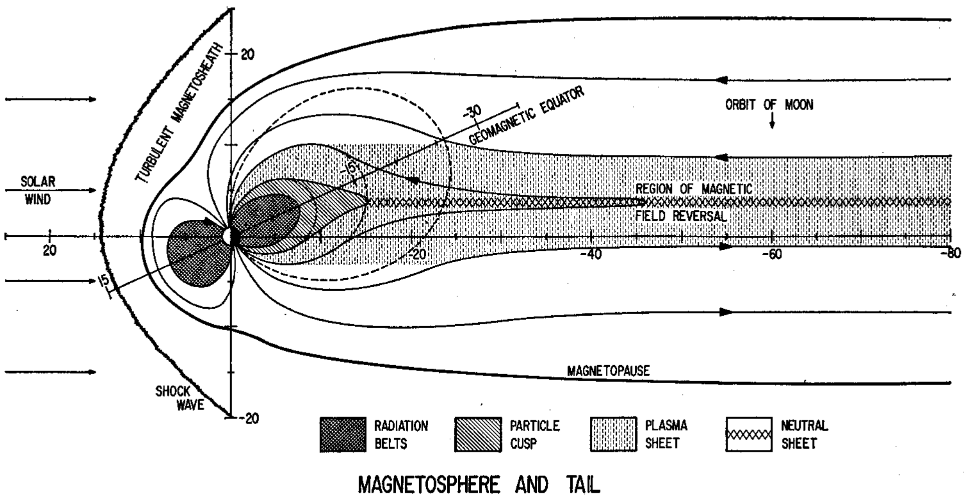

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TABLE 1. Trans-Magnetosphere Space Probe Experiments

Space Vehicle	Launch Date, day/mo/yr	Apogee, km	Perigee, km	Inclination to Equator, deg	Instruments for Low-Energy Plasma Studies
Luna 1	2/1/59				Charged particle traps.
Luna 2	12/9/59				Charged particle traps.
Explorer 12	16/8/61	83,600	6,700	33	CdS detector, spherical electrostatic analyzer.
Alouette 1	29/9/62	1,000	1,000	80	Station for ionospheric radio sounding, ULF radiation receiver.
Explorer 14	2/10/62	85,300	300	33	Spherical electrostatic analyzer.
Mars 1	1/11/62	Interplanetary probe			Charged particle traps.
Injun 3	13/12/62	2,785	237	70.4	Electron multiplier.
IMP 1	27/11/63	191,230	197	33	Charged particle traps (analyzer with a retarding potential and Faraday cup of modulation type), spherical electrostatic analyzer.
Electron 2	30/1/64	68,200	460	61	Charged particle traps. Spherical electrostatic analyzer.
Electron 4	11/7/64	66,235	460	61	Charged particle traps, spherical electrostatic analyzer.
Vela 2B	17/7/64	115,140	90,920	40	Spherical electrostatic analyzer.
OGO 1	5/11/64	150,000	280	31	Faraday cup (charged particle trap of modulation type), spherical electrostatic analyzer.
IMP 2	4/10/64	93,910	197	33	Charged particle traps: analyzer with a retarding potential and a Faraday cup of modulation type, spherical electrostatic analyzer.
Explorer 22	19/10/64	1,000	1,000	80	Cylindrical Langmuir probe.
Injun 4	21/11/64	2,495	530	81	Scintillation counter for measuring proton energies.
Zond 2	30/11/64	Interplanetary probe			Charged particle traps of integral and modulation types.
Vela 3A	20/7/65	115,840	106,370	35	Spherical electrostatic analyzer.
Vela 3B	20/7/65	122,080	100,570	34	Spherical electrostatic analyzer.
Alouette 2	29/11/65	9,980	500	80	Ionospheric radio sounding station.

TABLE 1 (*continued*)

Space Vehicle	Launch Date, day/mo/yr	Apogee, km	Perigee, km	Inclination to Equator, deg	Instruments for Low-Energy Plasma Studies
Luna 10	31/3/66	Moon's satellite			Ion trap, electron trap, a modulation-type trap for recording ions of thermal energies.
OGO 3	7/6/66	122,300	295	31	Faraday cup (a modulation-type charged particle trap), four cylindrical electrostatic analyzers.
Explorer 33	1/7/66	440,000	50,000	7	Charged particle trap of a modulation type.
Pioneer 7	17/8/66	Interplanetary probe			Faraday cup (charged particle trap of a modulation type), spherical electrostatic analyzer.
ATS 1	7/12/66	Synchronous orbit h = 35,800 km			Trap for low-energy ions.
Explorer 35	19/7/67	Moon's satellite			Faraday cup (a charged particle trap of a modulation type), retarding potential analyzer.

2. THE EARTH'S PLASMA ENVELOPE (THE OUTERMOST IONOSPHERE)

Let us begin with terminology. In this section of the paper data will be discussed concerning the properties of the plasma at an altitude ranging up to 20,000–30,000 km. This plasma is populated with electrons and protons with thermal energies not exceeding several electron volts.

In the literature, as has already been pointed out [*Gringauz,* 1967], many different terms were used for denoting this plasma: an ionized component of the geocorona [*Gringauz et al.,* 1960*a*], a protonosphere [i.e. *Geisler and Bowhill,* 1965], a magnetoionosphere [*Taylor et al.,* 1965], a plasmasphere [*Carpenter,* 1966], and an outermost ionosphere [*Gringauz,* 1967].

If, beginning with heights of 1500 to 2000 km (which are always related to the ionosphere), one measures the electron or ion densities from a vertically ascending rocket, the instruments will not record any peculiarity in plasma density variation up to the region of an accelerated reduction of charged particle density (a 'knee'). In other words, there is no boundary between the 'classical' ionosphere and the region under consideration, and no attempts have been made to define this boundary, even conditionally. Therefore, although the term 'plasmasphere' is becoming popular, the term 'outermost ionosphere' seems to me the more appropriate one for this region.

At present, there are some observations of both the ion and electron components of the outermost ionosphere which make it possible to speak with sufficient confidence on some of its properties. In particular, at middle geomagnetic latitudes and at geocentric distances from 3 to 6 R_E, a sharp drop occurs in the altitude distribution of charged particle density (the so-called 'knee' region). The boundary of the region lying below the knee shall be considered the boundary of the outermost ionosphere and termed a 'plasmapause,' following *Carpenter* [1966].

The first direct measurements of the density of positive ions in the outermost ionosphere were performed in 1959 by means of charged particle traps on the Soviet lunar vehicles Luna 1 and Luna 2 [*Gringauz et al.*, 1960*a*, *b*; *Gringauz*, 1961*b*]. These measurements showed that at altitudes of 20,000 km ($R \sim 4R_E$) there is a region of accelerated drop in charged-particle density and a specific 'plateau' in height distribution. For the first time it was possible to give a rough estimate of ion temperature T_i at $R \sim 4R_E$. We could state that T_i does not exceed tens of thousands of degrees.

Of very great significance in the studies of this region was the detection of this knee region in the equatorial height distribution of electron density n_e in analyzing the results of ground-based observations of whistlers [*Carpenter*, 1963*a*]. This work initiated a series of investigations accomplished personally by Carpenter or with his participation. From these studies statistically valuable data have been obtained that characterize the variation of the altitude of the knee region in the equatorial zone of the outermost ionosphere as a function of local time and geomagnetic activity.

Figure 2, taken from the first report by *Carpenter* [1963*a*, *b*], shows the n_e profile from whistler data. The open circles indicate the values of ion density at appropriate geocentric distances determined in 1959 from the data of the charged

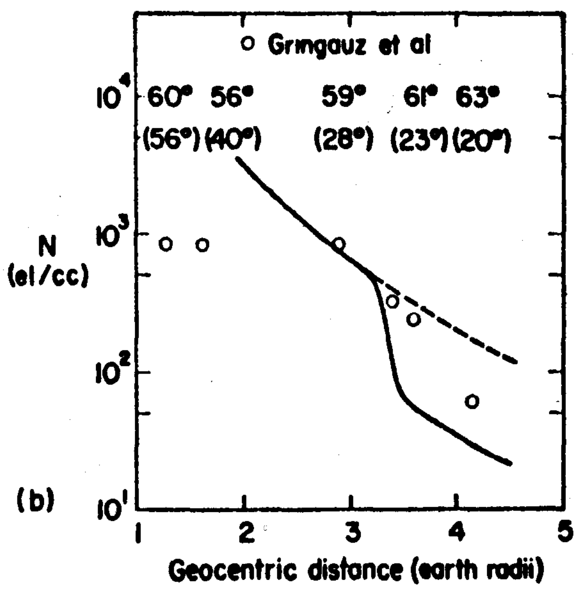


Fig. 2. Electron density n_e (whistler data) and ion density (Luna 2) as a function of geocentric distance. Open circles are Luna 2 data. In the upper part of the graph, values of the Luna 2 invariant latitude Λ (without brackets) and geomagnetic latitude (in brackets) are given. Electron densities are in the geomagnetic equatorial plane [*Carpenter*, 1963*a*].

particle traps aboard Luna 2. The author considered the agreement between these data satisfactory.

Discussing the difference between the data obtained by Luna 2 and Carpenter's results, *Obayashi* [1964] pointed out that the difference in altitude distributions of charged particle density might be due to the fact that the measurements refer to regions with different geomagnetic latitudes. The altitude distribution of the temperature of the ionospheric plasma may strongly depend on the geomagnetic latitude: at high latitudes the temperature may be higher because the thermal conductivity of the ionosphere is essentially anisotropic, and this may in turn affect the altitude distribution of charged particle density. *Carpenter and Smith* [1964] pointed out that the discrepancy between the n_e profile in Figure 2 (plotted from whistler data) and the n_i profiles relating to the equatorial plane (plotted from the data of Luna 2) may be due to the decrease in density at relatively low altitudes with an increase of geomagnetic latitude, since the measurements of n_i by Luna 2 started at the height of ~2000 km at a geomagnetic latitude of ~60°.

Subsequently *Carpenter* [1966] processed extensive experimental data on whistlers, recorded at high-latitude stations in the Antarctic and measured by hundreds of thousands of sonograms. Figure 3 gives average data on the position of the knee in the plane of the geomagnetic equator. The curve characterizing the average diurnal variations of plasmapause position for days with moderate geomagnetic activity has the following specific features:

1. The smallest geocentric distance of the knee region is observed in morning hours (at approximately 0600 LT) and is 3–3.5 R_E.

2. At approximately 1800 LT a sharp increase in the height of the knee regions occurs causing R to change from 3.5 to 5 R_E. The motion of the knee region downward is much slower and lasts roughly 10 hours.

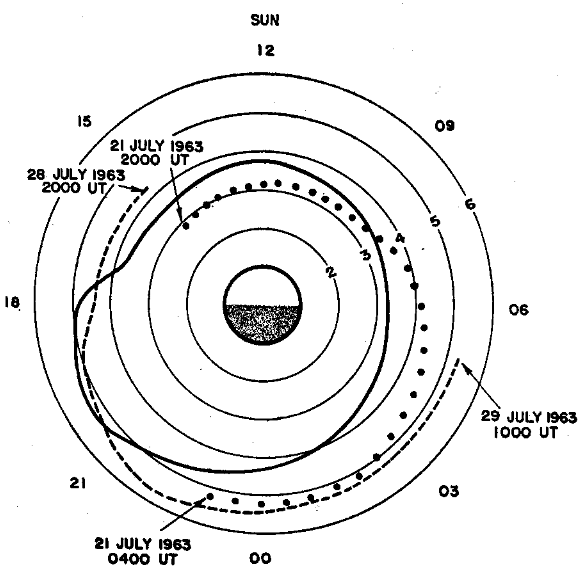


Fig. 3. Variations of the plasmapause position versus local time. Figures indicate distances in R_E. The solid curve corresponds to increasing magnetic activity; the dashed curve, to decreasing magnetic activity [*Carpenter*, 1966].

3. From 0600 LT to midday the height of the knee region rises smoothly.

In papers describing the knee, the strong dependence of the height of the knee on the level of geomagnetic activity was pointed out [*Carpenter,* 1963*a*, *b; Carpenter and Smith,* 1964]. Detailed data on this dependence were published later [*Carpenter,* 1966]. An example of such data is given in Figure 4 where it is evident that the growth of geomagnetic disturbances causes the knee to approach the earth. The author points out that the change in the level of geomagnetic disturbances affects the height of the knee, as a rule, in 6 hours.

The analysis of many data used by Carpenter, taking into account the results of mass-spectrometric investigations of ions [*Taylor et al.,* 1965], has enabled him to suggest a preliminary model for the distribution of thermal plasma around the earth. In cases of moderate geomagnetic activity, the projection of this envelope on the plane of the geomagnetic equator resembles a circle, except for the region between 1700 and 2400 LT (Figure 3). With an increase in geomagnetic activity, the envelope compresses and its asymmetry increases; with the decrease of K_p, the plasma envelope expands and its asymmetry decreases.

Figure 5 shows an idealized meridional projection of the day side of the plasma envelope (at ~1400 LT). The hatched region is limited by the magnetic shell $L = 4$ with electron density $n_e = 10^2$ cm^{-3}; outside this region $n_e \sim 1$ cm^{-3}. According to Carpenter, this region has a rather sharply pronounced boundary along the line of force $L = 4$ during low magnetic activity. At high latitudes,

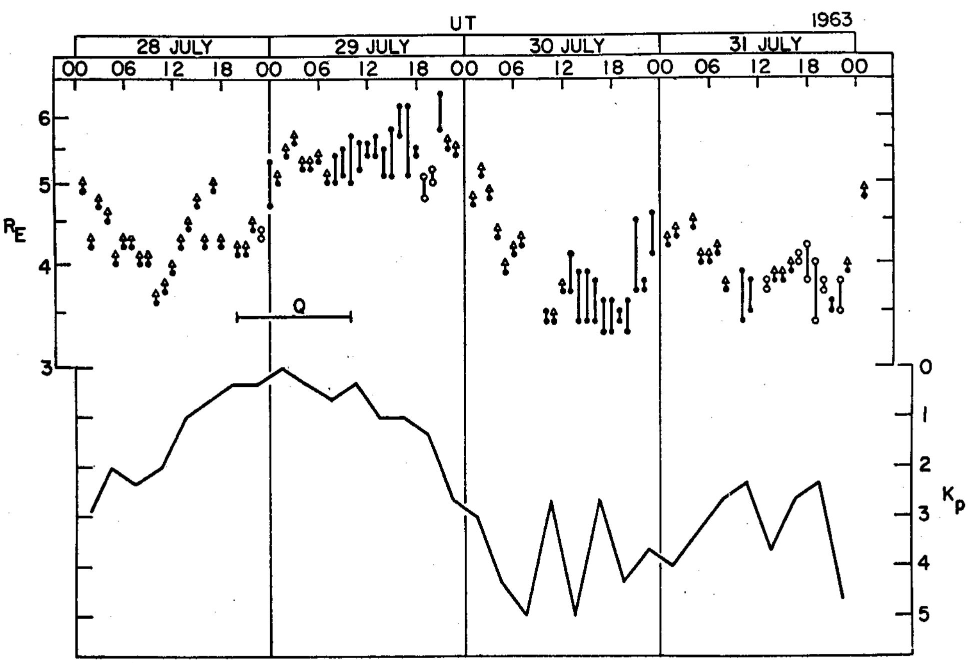


Fig. 4. Plasmapause position plotted as a function of geomagnetic activity during the period from July 28 to July 31, 1963. Time is UT [*Carpenter,* 1966].

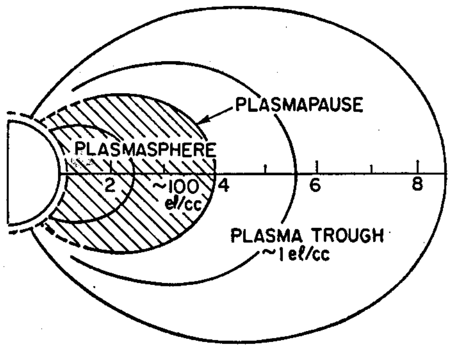


Fig. 5. Model of the thermal plasma distribution in the meridian cross section of the magnetosphere near 1400 LT (moderate geomagnetic activity: $K_p \sim 2 - 4$) [*Carpenter*, 1966].

however, the difference in n_e on both sides of this boundary can considerably decrease. In Figure 5 this section of the line of force is indicated by the dashed line. Averaging numerous results from the analysis of whistler records made at moderate geomagnetic activity, *Carpenter* [1966] showed that the altitude distribution has a sharp knee at geocentric distances of $\sim 4R_E$ by day and at night. However, if at night n_e varies by a factor of 30 to 100 within a distance of 0.15 R_E, this variation decreases by day as much as 10 times [*Angerami and Carpenter*, 1966].

Measurements of the ion component of the thermal plasma surrounding the earth by means of charged particle traps initiated by a Soviet lunar vehicle in 1959 were continued in 1964 by satellites of the Electron type. Some preliminary data obtained from Electron 2 relating to the equatorial regions of the outermost ionosphere were published in 1965 [*Bezrukikh and Gringauz*, 1965; *Gringauz et al.*, 1966*a*]. More detailed data are presented by *Bezrukikh* [1968]. Figures 6 and 7 give samples of the data from satellites of the Electron series. Figures 7*a* and *b* show that from the data obtained by satellites of the Electron type we may draw conclusions similar to those of Carpenter.

The ion components of the outermost ionosphere were also studied with the aid of an RF mass spectrometer of the Bennet type on satellites OGO 1 and OGO 3 in 1964 and 1966 [*Taylor et al.*, 1965, 1968]. On the same satellites

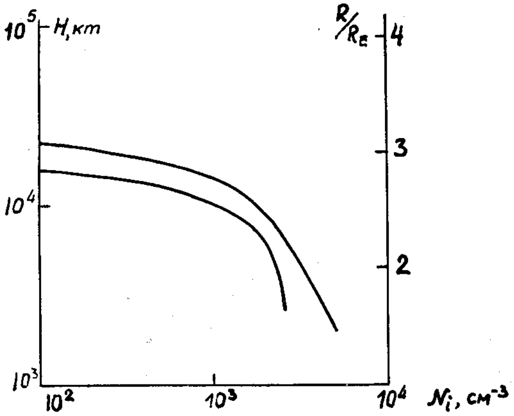
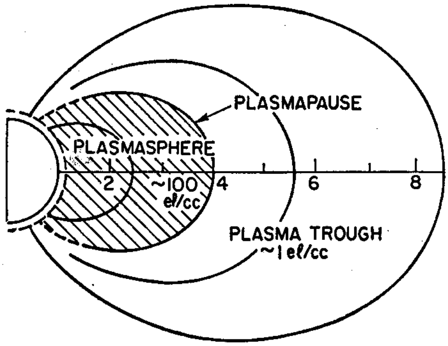


Fig. 6. Ion density n_i altitude distributions near the geomagnetic equatorial plane, measured by a charged particle trap on the Electron 2 satellite [*Bezrukikh and Gringauz*, 1965].



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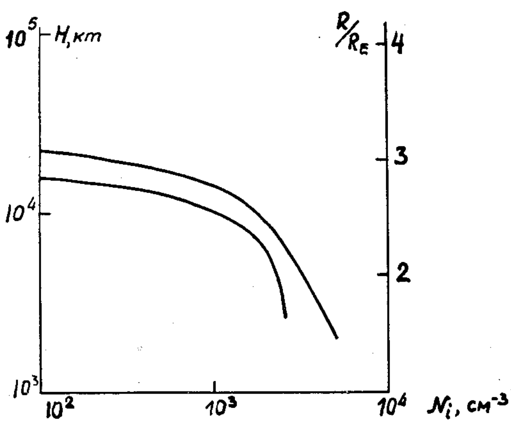

Fig. 6. Ion density n_i altitude distributions near the geomagnetic equatorial plane, measured by a charged particle trap on the Electron 2 satellite [*Bezrukikh and Gringauz,* 1965].

data on plasmapause positions were obtained by charged particle trap plasma detectors [*Vasyliunas,* 1968*b*]. In addition, data on the outermost ionosphere were obtained by charged particle traps on the IMP 2 satellite [*Serbu and Maier,* 1966; *Binsack,* 1967].

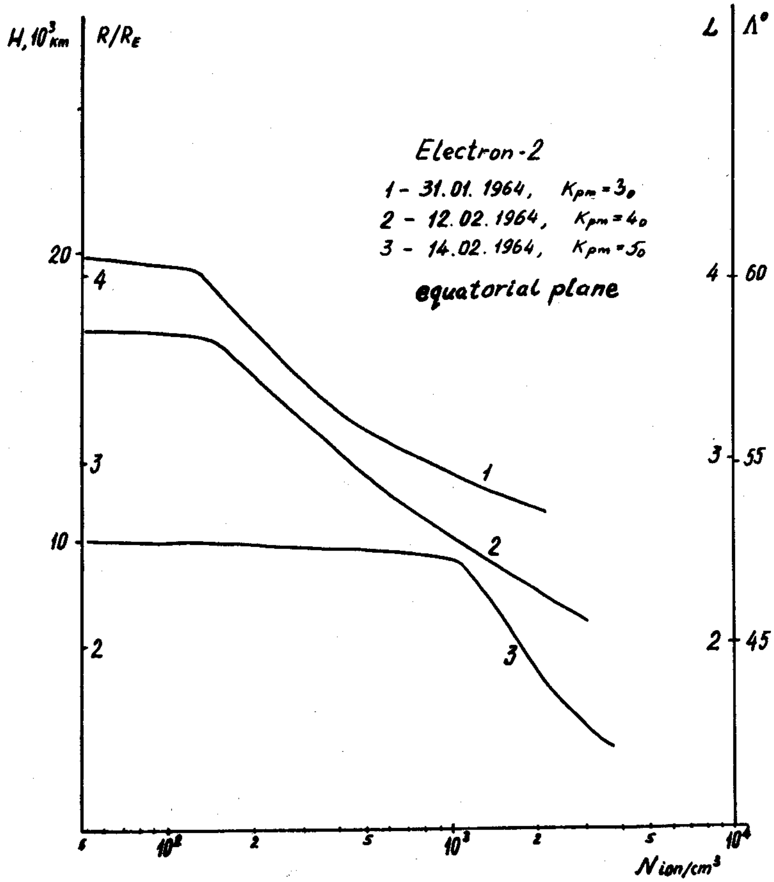

Fig. 7*a*. Ion density n_i versus altitude H, geocentric distance R, and the L coordinate (nighttime, January–February, 1964) [*Bezrukikh,* 1968].

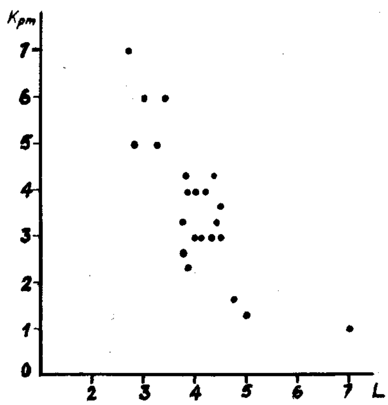

Fig. 7*b*. Correlation between the 'knee' position in the L coordinates and the maximum K_p index the day before the measurements (Electron 2 and Electron 4 satellite data) [*Bezrukikh,* 1968].

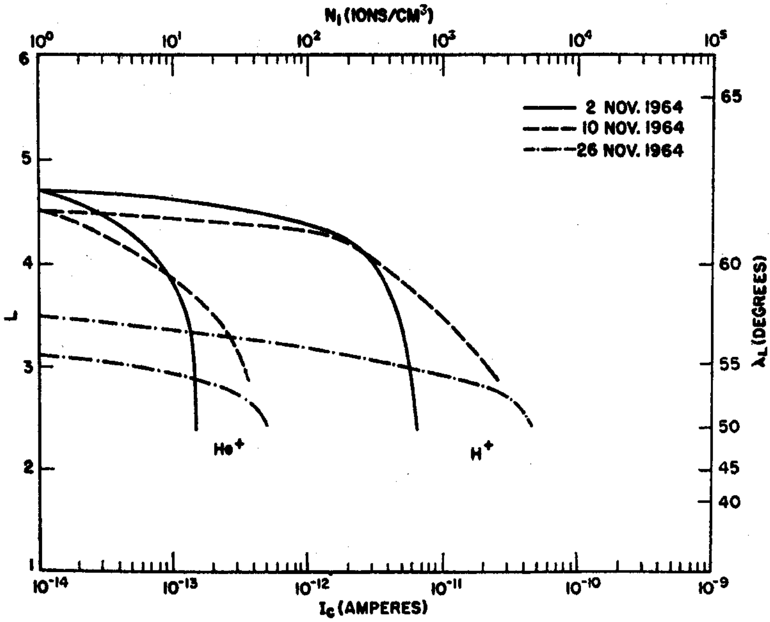

Fig. 8. Proton and helium ion densities, according to the OGO 1 mass spectrometer, plotted as a function of the L coordinate [*Taylor et al.,* 1965].

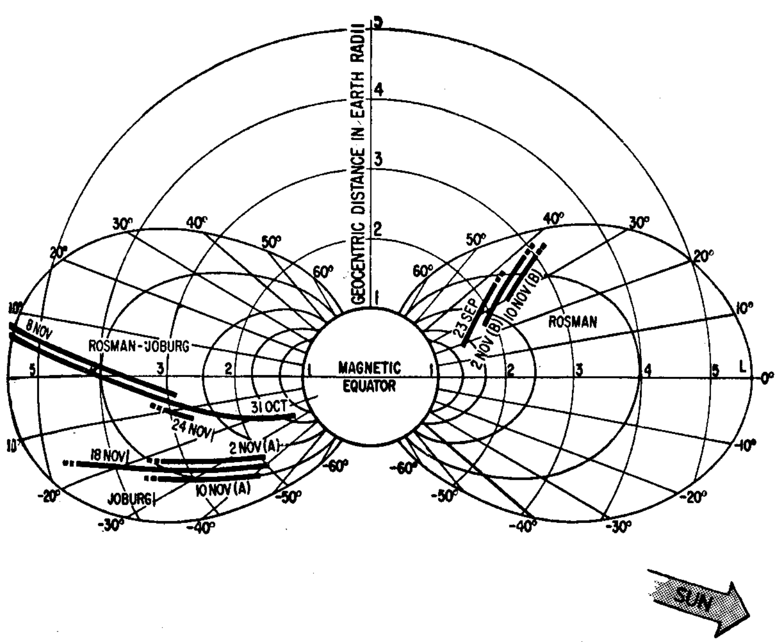

Fig. 9. Locations where decreases of proton current were observed during nine OGO 1 passes. The solid part of each curve indicates a region of gradual decrease in ion current with altitude; the beginning of the dashed part specifies the location of a rapid decrease in current [*Taylor et al.,* 1965].

Figures 8 and 9 show several results of ion mass spectrometric measurements from OGO 1 [*Taylor et al.,* 1965]. It followed from these measurements that in the overwhelming majority of cases the plateau in the altitude distribution of n_i goes down with an increase and up with a decrease of geomagnetic activity. The connection between the compression of the outermost ionosphere and geomagnetic activity was studied by *Taylor et al.* [1968], using data obtained in 1965–1966 from ion RF mass spectrometers flown on satellites OGO 1 and OGO 3. The authors conclude that there is an inverse correlation between the L coordinate of the plasmapause and the maximum K_p index for the 24-hour period preceding the measurements. During the events associated with the solar flares of June 15, 1965, and July 7 to 9, 1966, with $K_p > 5$, the plasmapause went down from $L = 6$ to $L \sim 3.3$.

During the flights of satellites OGO 1 and OGO 3, *Carpenter et al.* [1969] simultaneously and repeatedly observed the knee by three independent methods: from the analysis of whistlers recorded in the Antarctic, by means of the ion mass spectromet carried by the satellites, and from the measurements of VLF radiation made by the satellites. In the last method the intersection of the plasmapause by the satellite is characterized by a sharp change in the character of the received VLF radiation. The observed values of the L coordinate of the knee were between 3.2 and 5.5. Simultaneous measurements made on the earth and on the satellite, with a local time difference of about 1 hour, determine the same position of the plasmapause (within the limits of experimental error $\sim$0.2 R_E). The satellite measurements of the position of the plasmapause, made by means of a mass spectrometer and VLF receiver in cases described by the authors, show a discrepancy of $\sim$0.1 R_E.

These experiments show that the determination of the knee position is consistent between ground-based observations of whistlers and satellite measurements. They also show that we are correct in supposing that the plasmapause (at moderate geomagnetic latitudes) has the form of a geomagnetic shell.

On the satellites OGO 1, OGO 3, and IMP 2, plasma detectors developed at MIT were installed. These detectors were designed to measure electrons [*Binsack,* 1967; *Vasyliunas,* 1968*b*]. The analysis of the data of these instruments and of the specific features of the recording of charged particles has shown that, owing to some secondary processes (not treated here), the entry of the satellites into a zone of large positive ion densities, i.e., the crossing of the plasmapause, was easily determined. Comparison of the changes in the position of the plasmapause with changes of geomagnetic activity has led the authors to conclusions similar to those of Carpenter, Taylor, and others. In particular, Binsack thinks that under magnetically quiet conditions $L = 6$ corresponds to the plasmapause and that with an increase of K_p, the L coordinate of the plasmapause can be approximately described by an empirical formula $L = 6\text{–}0.6\ K_p$ where the K_p index corresponds to the time of measurements.

Note that on the same satellite, IMP 2, simultaneous measurements of electron and ion components of the earth's plasma envelope were carried out by means of charged particle traps, with the analysis of particle energies obtained by means of a retarding potential analyzer [*Serbu and Maier,* 1966, 1967]. In the interpretation of the data from this experiment, the authors did not detect the knee in the distribution of charged particle density. We have already pointed out that this result contradicts some other independent observations [*Gringauz,* 1967]. Now we may add that this result conflicts even with the simultaneous observations carried out on the same space vehicle [*Binsack,* 1967]. The reason for this disagreement requires clarification.

From the same measurements obtained from IMP 2, Serbu and Maier have concluded that for $4\ R_E < R < 10\ R_E$ the ion temperature considerably exceeds the electron temperature ($T_e \sim$ 1–2 ev, $T_i \sim$ 4–8 ev). Note that these values of T_i essentially exceed the estimates of the upper limit of T_i at $R < 5.5\ R_E$ from the data of Electron 2 [*Bezrukikh et al.,* 1967]. From theoretical temperature models of the outermost ionosphere [*Geisler and Bowhill,* 1965; *Gliddon,* 1966; *Nagy et al.,* 1968] it follows that in the absence of selective sources of heating and cooling of electron and ion gases, T_i should not exceed T_e. A satisfactory mechanism for such selective heating has not been found so far.

Investigations of the lower part of the ionosphere conducted in recent years have shown that the geomagnetic field to a great extent controls the behavior of the ionosphere. Some ionospheric peculiarities associated with the transportation of charged particles along the geomagnetic tubes of force have been indicated in the review paper by *Roederer* [1967] devoted to phenomena at magnetically conjugate points. Considerable latitudinal gradients have been detected at high latitudes associated with the trough of the electron density, at heights from 1000 km to the maximum of the *F* layer, from the data of ionograms obtained from the satellite Alouette 1 [*Thomas and Sader,* 1964], and at the height of ~1000 km from the results of the Langmuir probes on Explorer 22 [*Brace and Reddy,* 1965]. Surprisingly low values have been measured by high-latitude ionograms obtained from Alouette 2 at altitudes of 1500–3000 km, where at $L > 6$ densities have been observed between 8 and 100 cm^{-3}. The boundary of the region where $n_e \sim 30\ cm^{-3}$ is shifted in geomagnetic latitude by 8° from noon to midnight [*Hagg,* 1967]. The authors of these experiments note a similarity of the above phenomena detected in high-latitude regions and low altitudes, with the knee observed at high altitudes and low geomagnetic latitudes. Although some connection between these phenomena seems clear to us, it nevertheless is not a comprehensive explanation of the existence of the knee, because the peculiarities of the high-latitude ionosphere at low altitudes also need an adequate explanation. In addition, as has been pointed out by *Angerami and Carpenter* [1966], there are incongruities between the variations of the position of the knee in the equatorial plane and the variations of the lower part of the ionosphere at high latitudes.

In 1961 Axford and Hines' theory of high-latitude geophysical phenomena and magnetic storms was published; it suggested a model for the magnetosphere that contained a convectively moving plasma in its outer parts. A viscous-like interaction of the magnetospheric plasma with the solar wind was assumed to be the source of convection. As a result of the convective motion of the plasma in the magnetic field, electric fields are produced in the magnetosphere. At lower L values a forbidden zone is formed, into which the plasma taking part in the convection does not penetrate. The size of this zone is determined by a geomagnetic latitude of 62°, which corresponds to ~4.5 R_E in the equatorial plane. It is clear that the plasma density should be a different function of geocentric distance inside the forbidden zone than outside.

In the same year, *Dungey* [1961] suggested a model of the magnetosphere with convective motion of the magnetospheric plasma caused by reconnection of the lines of force of the magnetospheric tail with those of the interplanetary magnetic field.

Thus, soon after the publication of the first experimental data obtained by lunar vehicles on the distribution of charged particles at distances of several R_E and independent of these data, theoretical arguments were published which suggested that an abrupt change occurred in plasma distribution at distances of the order of $4.5R_E$. Subsequently some theoretical papers were published in which convection in the magnetosphere outside of the forbidden zone was commonly assumed. In all these papers the boundary of this zone is directly identified with the knee [*Block,* 1966; *Nishida,* 1966; *Dungey,* 1967; *Samokhin,* 1966, 1967*a, b,* 1968; *Brice,* 1967; *Kavanagh et al.,* 1968]. These authors differ in their choice of causes producing a convective motion of the magnetospheric plasma and the forbidden zone and in the configurations of the postulated magnetospheric electric fields. In some of them the earth's rotation is significant; in others it is not taken into account. Nevertheless, the convective motion of plasma is one of the main specific features of magnetospheric models considered in these papers.

Until recently, belief in the existence of convective circulation of the plasma in the magnetosphere was based on indirect data (for example, ground-based observations of the drifts of auroral and radio auroras and geomagnetic disturbances at high latitudes). The latest measurements conducted by the geostationary ATS 1 satellite apparently give direct experimental proof of the convection [*Freeman,* 1968; *Freeman and Maguire,* 1967; *Freeman et al.,* 1968]. The existence of the motion (with a bulk velocity of ~30 km/sec) of magnetospheric ions with thermal energies of ~1 ev is established. According to the authors' estimates, this motion corresponds to an electric field with $E \sim 5$ mv/m directed across the magnetosphere from the dawn to the dusk side.

In *Dessler and Michel*'s [1966] model the distribution of plasma density in the magnetosphere is explained without the use of convective motion on the basis of the evaporation of plasma from the polar zone of the ionosphere along the lines of force of the open tail of the magnetosphere.

In the latest papers by *Axford* [1968] and *Banks and Holzer* [1968], arguments and calculations are advanced in favor of a supersonic flow of plasma from the polar regions of the ionosphere (called a 'polar wind' by them) which may also explain the formation of the knee. A discussion of these papers is a worthy subject for a special review paper.

In summing up, it may be stated that the combination of experimental data now available on the cold (thermal) plasma in the magnetosphere gives a basis for thinking that there is a characteristic surface (the boundary of the outermost ionosphere) that is, the plasmapause, which seems to separate the magnetospheric plasma taking part in the convection motion from the plasma rotating with the earth. The plasmapause is situated inside the outer radiation belt. With an increase of geomagnetic activity, it compresses (approaches the earth); with a decrease, it expands.

Let us return to the model suggested by *Carpenter* [1966] determined in the equatorial plane (Figure 3) and in the meridional plane (Figure 5); while using this model, we should bear in mind the following:

1. The method used for determining the electron density n_e from whistler data gives values only in the equatorial plane.

2. While constructing the model of the earth's cold plasma envelope in the meridional cross section, Carpenter partly used the results of *Taylor et al.* [1965] obtained from OGO 1. However, this satellite, as well as the satellites IMP 2 and OGO 3, has only a small inclination to the equator; therefore, the data obtained relate to the region of geomagnetic latitudes $\lesssim 45°$. Apparently, for this reason, the author of the model pointed out that a portion of the boundary line of force, indicated by the dashed line, corresponds to the region where the structure of the knee is insufficiently known.

Note that the pronounced knee is absent in the profiles of the charged particle density obtained in 1964 at geomagnetic latitudes above 45° by means of charged particle traps on the Electron 4 satellite [*Bezrukikh,* 1968].

It should also be noted that positive ion densities from the data of mass spectrometers on OGO satellites contain an uncertainty of a factor of 5, owing to difficulties in calibrating the values of measured currents in the particle density [*Taylor et al.,* 1965] and that similar difficulties were encountered in processing data obtained from satellites of the Electron series [*Bezrukikh and Gringauz,* 1965]. Therefore, one should not regard the model under consideration as a final one; the author himself calls it a preliminary model.

3. FLUXES OF LOW-ENERGY PARTICLES ($E \lesssim 40$ KEV) IN THE TRAPPED RADIATION ZONE

Particle fluxes in the radiation belts were greatly overestimated by the authors of the first American and Soviet experimental investigations whereas particle energies were underestimated. It was thought that in the outer belt the electron flux was 10^{10}–10^{11} cm^{-2} sec^{-1} with energies $E > 20$ kev. Such estimates were made on insufficiently-based suppositions regarding the energy spectrum of the particles studied when interpreting the instrument readings. Although the data of the charged particle traps on Luna 2 showed that the total electron fluxes in the outer radiation belt could not exceed 2×10^7 cm^{-2} sec^{-1} [*Gringauz et al.,* 1960*a*; *Gringauz et al.,* 1963], other experimenters up to 1962–1963 overestimated the fluxes by 3 orders of magnitude.

Fluxes so large caused many authors to think that energetic charged particles, trapped in the outer belt, might cause magnetic storms, that their precipitation into the atmosphere might directly produce auroras, etc.

When reduced estimates of electron fluxes and their harder energy spectrum became universally accepted, interest in the outer radiation belt as the cause of other major geophysical phenomena was considerably weakened. It seems to be rising again, now that large fluxes of low-energy particles have been detected in the outer belt. These fluxes vary strongly in time and their energy density is sometimes very high.

Let us begin with the inner radiation belt ($L \lesssim 2$). Publications on low-energy plasma fluxes there are very scarce. *Freeman* [1962] considered the results of observations from the CdS crystal detector on Injun 1 at a height of 1000 km at $L < 1.7$ as evidence of protons with energies 0.5 kev $< E <$ 1 Mev carrying an energy flux of 50 erg cm^{-2} sec^{-1}. *Frank and Swisher* [1968], on the basis of electrostatic analyzer data obtained on OGO 3 in 1966, noted that at $L < 1.7$ the maximum energy fluxes of recorded protons with energies from 100 ev to 50 kev are 10–100 times lower than those indicated by Freeman. They also pointed out that results from Injun 4 in 1965 (unpublished) showed the energy flux of protons with energies $E >$ 30 kev in the inner belt to be also 10 to 100 times lower than Freeman's value. As measurements on the above satellites were conducted at greatly differing time intervals, the discrepancy of the results may be due to changes in the characteristics of the inner belt from 1961 to 1966.

The only results of measurements of the fluxes of protons with energies $E \lesssim$ 50 kev with $L < 2$ reported so far relate to a period of geomagnetic disturbances and are given in Figure 10; upper limits are indicated [*Frank*, 1968]. No measurements of fluxes of electrons with energies $E <$ 50 kev in the inner radiation belt have been published.

Information on the low-energy plasma in the outer radiation belt is more plentiful. During the flight of Luna 1 in January 1959, charged particle traps, starting at the geocentric distance of $\sim$5 R_E, detected electron fluxes of $\sim 2 \times 10^8$ cm^{-2} sec^{-1} with energy $E >$ 200 ev, exceeding (by about an order of magnitude) the fluxes of high-energy electrons in the maximum of the outer radiation belt [*Gringauz et al.,* 1960*b*]. The analysis showed that these fluxes were partly recorded in the morning part of the magnetosphere inside the radiation belt.

Freeman et al. [1963] mentioned that on Explorer 12 in the daytime sector

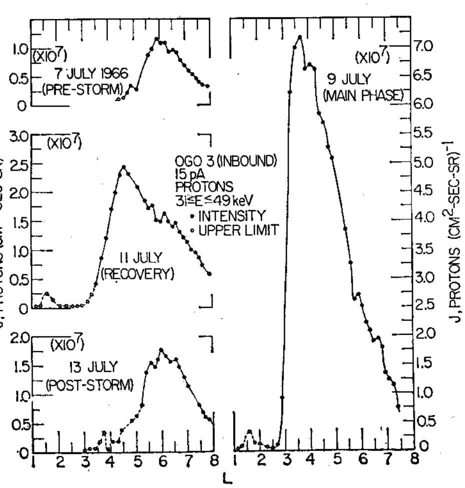

Fig. 10. Fluxes of protons with energy $E < 50$ kev during a magnetic storm according to OGO 3 electrostatic analyzer, plotted as a function of the L coordinate [*Frank*, 1968].

of the magnetosphere low-energy electrons were sometimes observed with maximum fluxes at $R \sim 7\ R_E$, although in most cases these electrons were absent. The authors did not give a more detailed description of these observations.

During some passes of Electron 2 through the inner radiation belt, a charged particle trap recorded considerable fluxes of electrons (up to 3×10^8 cm^{-2} sec^{-1}) with energies 100 ev $< E <$ 50 kev. Cases were also recorded (during other passages of the satellite) when the aforementioned electron fluxes were lower than the instrument's sensitivity, i.e. lower than 2×10^7 cm^{-2} sec^{-1} [*Bezrukikh et al.*, 1965; *Gringauz et al.*, 1966*a*]. In these as well as in other cases, the fluxes of electrons with energies $E >$ 100 kev trapped in the outer radiation belt that were measured and described by *Vernov et al.* [1965*a*] and *Kuznetsov et al.* [1965] were nearly constant (their magnitudes varied within about ±10%). This circumstance enabled the authors of the observations of low-energy electron fluxes

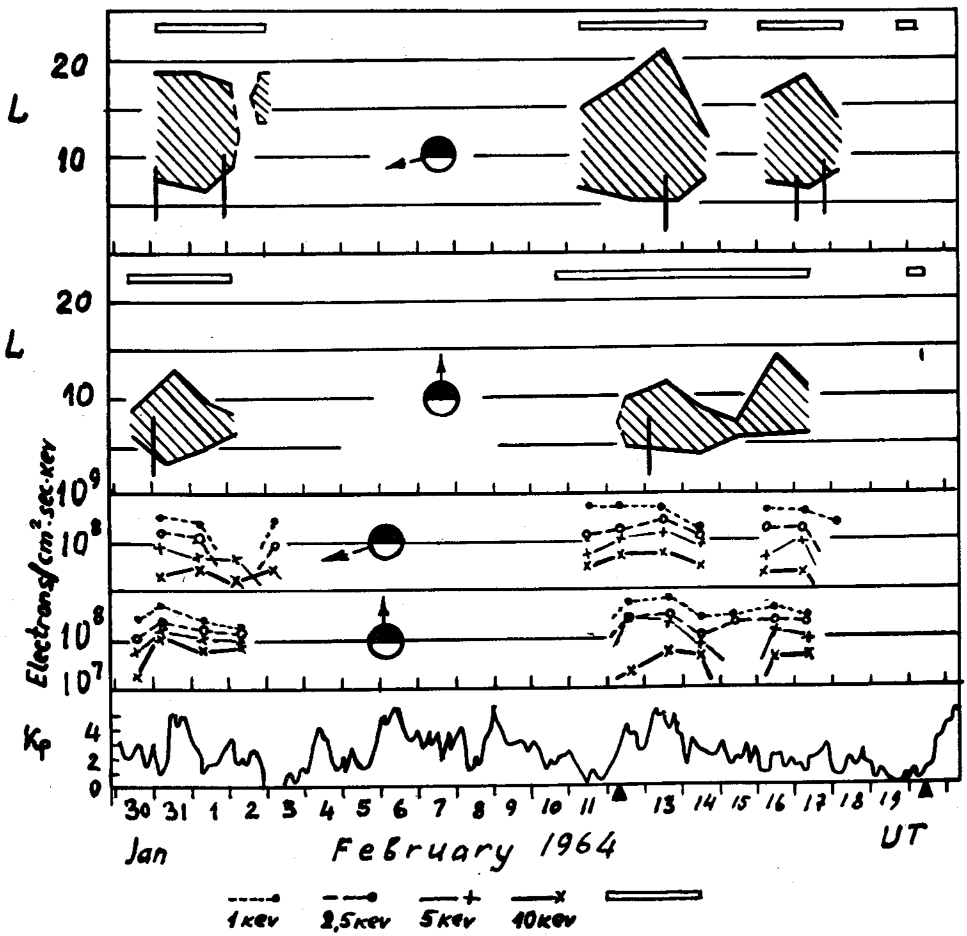

Fig. 11. Regions of increased low-energy electron flux plotted in L coordinates and fluxes in different energy ranges according to the Electron 2 spherical electrostatic analyzer data. Solid vertical lines correspond to the outer radiation belt position [*Vernov et al.*, 1965*b*].

to conclude that a soft electron component of the outer radiation belt exists which differs from the energetic trapped radiation in its great variability.

This conclusion was confirmed by the results obtained from the same satellite by means of the electrostatic analyzer. Some data are shown in Figure 11 [*Vernov et al.,* 1966], complemented by indications of the boundaries of the outer radiation belt by measurements of particles with energies $E > 100$ kev. It can be seen that fluxes of particles with energies from 0.1 to 10 kev, recorded in some cases inside the radiation belt, are absent during other passes.

Figure 12 shows for several passes of the satellite, fluxes of soft electrons as a function of L coordinates and of local time, as described by *Bezrukikh et al.* [1965] and *Gringauz et al.* [1966*a*]. Black circles and squares connected with dashes show the values of L and T during the satellite's passes when fluxes of soft electrons were recorded equal to 0.5 of the maximum value of the flux observed during this pass. Crosses indicate the boundaries of the outer radiation belt determined from a sharp drop in the fluxes of electrons with energies $E >$ 100 kev [*Kuznetsov et al.,* 1965]. The crossing of the outer boundary of the outer belt in no way affected the current of the charged particle trap. Electron fluxes were recorded outside the belt, too.

Frank [1966] reported on Explorer 12 (CdS detector) observations of time variations of the intensities of low-energy electrons in the outer radiation belt during geomagnetic storms. He states that at the commencement of strong geomagnetic storms on October 1 and October 29, 1961, in the region $L = 2.8$–4, the electron energy flux in the range 100 ev $< E <$ 40 kev sharply increased, reaching a maximum of 1000 erg cm^{-2} sec. No estimates of the increase in particle flux were made. Frank supposed that the recorded low-energy electrons produce a ring current, with a center at $L = 3$, which is partly responsible for the main phase of magnetic storms.

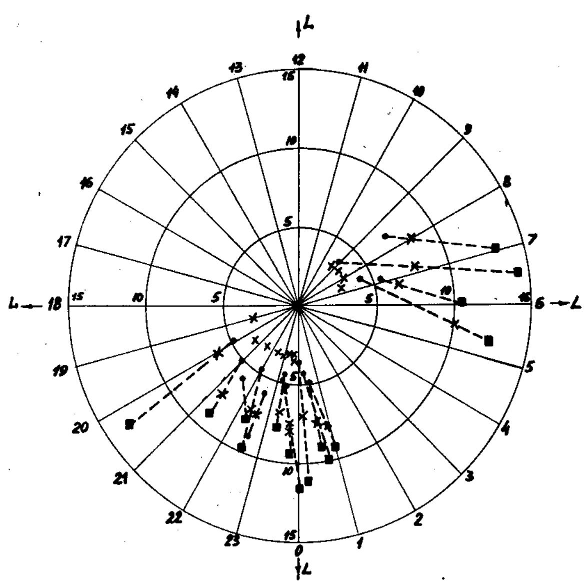

Fig. 12. Values of L coordinates and local time corresponding to the registration of electron fluxes with energy $E > 100$ ev by means of the charged particle trap during several Electron 2 passes. (For details, see text.)

In 1966 some results on fluxes of electrons with energies of 50 to 100 kev on Explorer 14 [*Pizzella et al.*, 1966] were also published. The measurements were made with a photomultiplier with a periodically varying absorber, and with a collimator that enabled the experimenters to measure the pitch angles of impinging electrons. Records were taken on the morning side of the magnetosphere (local time 0800–1000). High-energy particles were also recorded.

They conclude that there is a region of trapped electrons with average energies of about 10 kev and a maximum intensity of about 10^9 cm^{-2} sec^{-1} at $L = 8$. The maximum flux and the region's position in L coordinates vary strongly in time. These electrons are trapped since they exist deep in the morning part of the magnetosphere (the boundary of the magnetosphere was $L = 11$), and their pitch angle distribution is typical of trapped particles. The authors point out that the energy spectrum of these electrons has a discontinuity, as compared with electrons of smaller L. Therefore, these electrons should not be regarded as the 'tail' of more energetic trapped electrons; they have other origins and lifetimes. They were recorded during some but not all of the satellite passes.

Pizzella and co-authors maintain that these electrons correspond to electrons detected with charged particle traps on Luna 1 on January 2, 1959 [*Gringauz et al.*, 1960*b*], when the inner boundary of the zone of these electrons was at $L = 5$ at the geomagnetic latitude of $\sim 20°$ and the local time was approximately the same as in the measurements described. The experiments stress the lack of evident correlation between the measured magnitudes of electron flux and the geomagnetic conditions. A detailed correlation analysis was not made by them, owing to the limited amount of data studied.

Comparing the data of Pizzella and co-authors with the aforementioned fluxes of electrons with $E > 100$ ev on Electron 2, it may be noted that measurements performed on Electron 2 include some obtained during the morning, as on Explorer 14 (see Figure 12). In both series of measurements, electron fluxes were observed that varied greatly and sometimes considerably (by more than an order of magnitude) exceeded the high-energy electron fluxes of the radiation belt. These common features suggest that the fluxes of electrons with average energies of 5 to 10 kev measured on Explorer 14 in the outer radiation belt are of the same origin and possess the same properties as electrons recorded in the outer belt by Electron 2 (as on June 1).

The measurements of charged particle fluxes with energies of the order of hundreds and thousands of ev were also conducted on satellites OGO 1 and OGO 3 which crossed the outer radiation belt. The plasma detectors developed by MIT (charged particle traps of the modulation type), recording electrons with energies from 40 ev to $E \lesssim 2$ kev, had relatively low sensitivities. These instruments did not detect electron fluxes in the evening and night sectors of the outer radiation belt [*Vasyliunas*, 1968*b*].

OGO 3 also carried electrostatic analyzers of protons and electrons with energies from ~ 100 ev to ~ 50 kev, with sensitivity considerably exceeding that of earlier instruments for studying low-energy plasma in the radiation belts [*Frank*, 1967*b*, *c*]. Figure 13 gives the energy spectra of low-energy electrons obtained in the outer radiation belt at various magnetic shells ($3.4 \leq L \leq 8$)

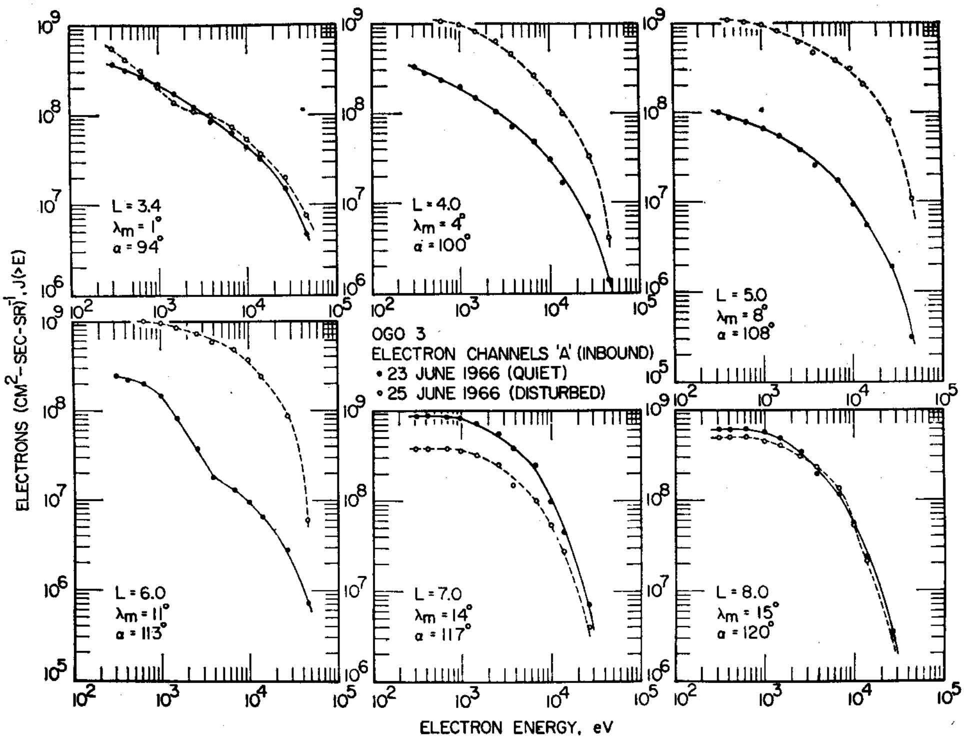

Fig. 13. Integral energy spectra of low-energy electrons according to the OGO 3 electrostatic analyzer [*Frank,* 1968].

on June 23, 1966 (a magnetically quiet day), and on June 25, 1966 (during strong magnetic activity). As is seen from the graphs in both cases, at all indicated values of L considerable electron fluxes were recorded, with the maximum in the energy range from several hundreds of ev to 1 kev. A sharp increase of electron flux accompanies a geomagnetic disturbance. Figure 14 presents an electron spectrum obtained at $L = 3.9$ on June 15, 1966, in which fluxes of electrons with energies of 10^3 to 10^4 ev are several orders of magnitude lower than in the previous figure [*Frank,* 1968].

These data confirm the presence of a very variable (in time) soft electron component of the outer radiation belt and for the first time give detailed energy spectra of the particles of this component.

On OGO 3, unique data on the soft proton component of the outer belt were also obtained. Earlier, low-energy charged particle detectors on satellites, which crossed the zone of trapped radiation, including electrostatic analyzers on IMP 1 satellites [*Wolfe et al.,* 1966*a*] and on Electron 2 [*Vernov et al.,* 1966], were not sufficiently sensitive and did not record positive ions in the radiation belts; thus they permit determination of only rough upper limits of the ion fluxes. Samples of determinations of fluxes of protons with $E < 49$ kev at $3 < L < 8$, from Frank's analyzer data, have already been given in Figure 10.

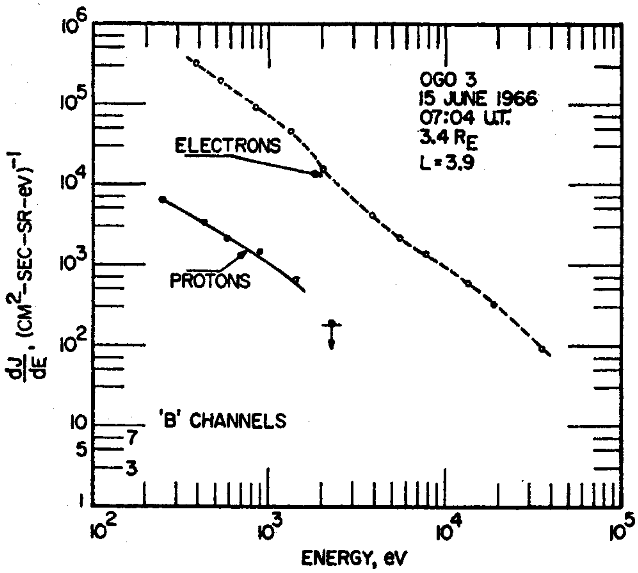

Fig. 14. Electron energy spectra according to the OGO 3 electrostatic analyzer [*Frank*, 1968].

An example of the differential energy spectrum of such protons when $L = 3.9$ (together with the simultaneously obtained electron spectrum) is given in Figure 14.

From analysis of Electron 2 magnetic field measurements, *Dolginov et al.* [1965] deduced the existence of a ring current created by low-energy protons in the outer radiation belt. The authors mentioned the absence of direct information about these protons. *Cahill* [1966] observed a strong inflation of the magnetic field from on Explorer 26 data taken during the April 1965 magnetic storm. This inflation was attributed to the development of a ring current of charged particles centered at $L = 3.5$ on the equator, with a decay time constant of about 4 days.

The analysis of considerable variations in the fluxes of low-energy protons and electrons in the outer radiation belt in June and July 1966 during moderate magnetic storms led *Frank* [1967*c*] to the conclusion that the total energy of these particles during the increase of these fluxes is sufficient to account for the decrease of the magnetic field at low and middle latitudes observed on the earth's surface; also, it is precisely these particles that create an extraterrestrial current ring during a storm. This ring is similar to that suggested by *Chapman and Ferraro* [1932]. The estimate showed that the following total energies of particles with 200 ev $\lesssim E \lesssim$ 50 kev enclosed between the magnetic shells $L = 1$ and $L = 8$ corresponded to the observed D_{st} disturbance of -50 gammas: for protons 2.1×10^{22} ergs and for electrons 5.3×10^{21} ergs. The observed lifetimes τ of protons with energies of 30–50 kev during a rapid decrease of their flux after the main phase of a magnetic storm were of the order of 10 hours. *Swisher and Frank* [1968] showed that these values of τ can be explained by the process of charge exchange with exospheric hydrogen atoms.

4. FLUXES OF LOW-ENERGY CHARGED PARTICLES BEYOND THE RADIATION BELTS

As was mentioned in the introduction, outside the boundaries of the outer radiation belt, fluxes of low-energy electrons with $E > 200$ ev were detected from the first lunar vehicle in 1959 [*Gringauz et al.,* 1960*a, b*; *Gringauz,* 1961*b*]. In their intensity these fluxes considerably (by not less than an order of magnitude) exceeded fluxes of electrons in the outer belt with energies $E > 50$ kev.

Beginning with 1961, such fluxes were observed on some Soviet and U. S. space vehicles which will be mentioned below. Data on the orbits of these vehicles were summarized in Table 1.

The outermost belt of charged particles (by which was meant in 1961 an intermediate zone between the earth's radiation belts and the solar wind) now includes, as has become clear in recent years, the following: (1) on the noon side, a transitional zone, or magnetosheath, between the front of a shock wave (produced by a supersonic flow of solar plasma around the geomagnetic field) and the magnetospheric boundary or 'magnetopause'; and (2) on the night side, a plasma sheet inside which there is a magneto-neutral sheet [*Gringauz and Khokhlov,* 1965; *O'Brien,* 1967*a, b*]. The present paper contains only brief information on the plasma in the magnetosheath (although it is undoubtedly described in the paper at this symposium devoted to the interaction of the solar wind with the magnetosphere). It was initially included by us in the outermost belt of charged particles because if low-energy plasma fluxes are injected into the magnetosphere through the neutral points (as is assumed by some authors, for instance, *Pletnev et al.* [1965]) then the undisturbed solar wind will not be their source. Rather, the thermalized plasma of the transition or magnetosheath layer, bordering the magnetosphere, will be the source.

The physical nature of the fluxes of low-energy charged particles in different regions of the magnetosphere and near it was clarified to a great extent by magnetic measurements in circumterrestrial space. These data led to the detection of theoretically predicted major characteristic surfaces [e.g. *Axford,* 1962] —the front of a shock wave and the boundary of the magnetosphere (magnetopause) from Explorer 12 [*Cahill and Amazeen,* 1963] and IMP 1 [*Ness et al.,* 1964] and the magneto-neutral sheet from IMP 1 [*Ness,* 1965]. As was mentioned above, Figure 1 corresponds to modern concepts of the geometry of the near-earth magnetic field.

During repeated crossings of the day portion of the magnetopause by Explorer 12 in 1961, a CdS crystal detector, sensitive to low-energy charged particles, obtained results, which were interpreted as indicating the existence of electrons with energies of 200 ev $\lesssim E \lesssim$ 40 kev with fluxes of 10^9 to 10^{10} cm^{-2} sec^{-1} in the transitional layer [*Freeman et al.,* 1963].

In 1963 and 1964 on the IMP 1 satellite, when it crossed the magnetosheath, fluxes of $\sim 10^8$ cm^{-2} sec^{-1} of electrons with energies $E > 100$ ev [*Serbu,* 1965], fluxes of $\sim 10^8$ cm^{-2} sec^{-1} of electrons with energies $65 \lesssim E \lesssim 210$ ev, and spectra of positive ions in the transition layer [*Bridge et al.,* 1965] were measured. Positive ion spectra were also measured from IMP 1 by *Wolfe et al.* [1966*a*].

Subsequently, characteristics of fluxes of low-energy charged particles in the magnetosheath were repeatedly measured, in particular by electrostatic analyzers of positive ions on Vela 2 satellites [*Gosling et al.*, 1967]. The data obtained by means of satellites following IMP 1 may be briefly summed up as follows: in the transitional layer there are electrons with energies $E > 100$ ev [*Serbu*, 1965] and in the range of $165 \lesssim E \lesssim 210$ ev [*Bridge et al.*, 1965] with fluxes of $\sim 10^8$ cm^{-2} sec^{-1}, which are absent in the undisturbed solar wind. The energy spectrum of electrons in the magnetosheath from Vela 2 data is shown at the top of Figure 15. The proton component of the plasma of the solar wind is characterized by the following changes behind the front of a shock wave: the energy spectrum considerably expands, the directed velocity drops by about a factor of 2, the density increases roughly twofold, and the temperature increases approximately five times. The kinetic energy of protons in the magnetosheath is roughly half as much as in the undisturbed solar wind. Apparently the loss is due to the heating of electrons and the generation of hydromagnetic waves in the magnetosheath [*Wolfe et al.*, 1966*b*]. It is worth noting that immediately after the first experiments on lunar vehicles [*Gringauz et al.*, 1960*b*], *Shklovsky et al.* [1960] explained the formation of fluxes of electrons with energies $E > 200$ ev beyond the trapped radiation zone by the transfer of solar wind proton energy to electrons with the plasma of the solar wind incident on the geomagnetic field.

The proton energy spectra obtained during a short period of time on October 4 and 5, 1964, from Vela 2*B* [*Gosling et al.*, 1967], IMP 2, and OGO (EGO) 1 at different sections of the transition sheet are also shown in Figure 15 [*Wolfe et al.*, 1966*b*].

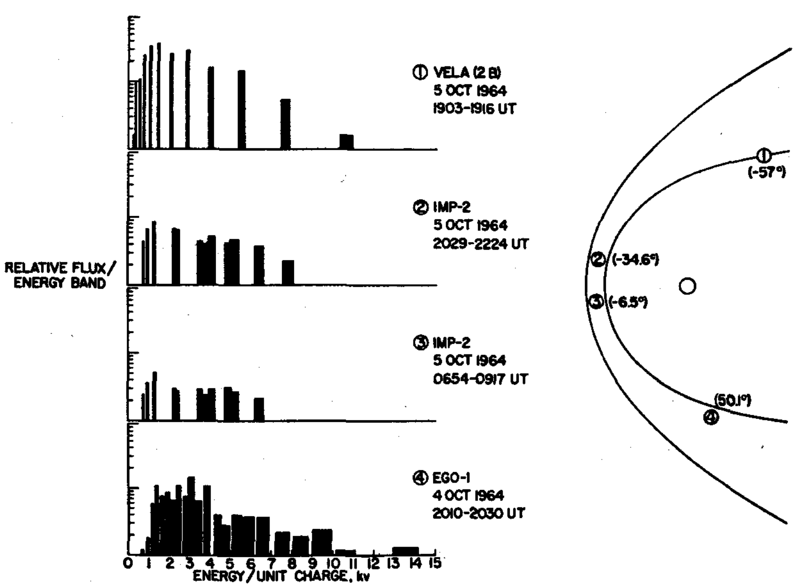

Fig. 15. Energy spectra of protons measured in the magnetosheath with different satellites [*Wolfe et al.*, 1966*b*].

We now come to the night magnetosphere. Measurements conducted by CdS crystals from Explorer 12 confirmed the existence of electron fluxes with energies $E > 200$ ev beyond the boundary of the outer radiation belt in the night portion of the magnetosphere. The distribution of electrons with energies 200 ev $\lesssim E \lesssim$ 40 kev in the equatorial plane of the magnetosphere, as it was seen in 1964, taking into account data of Explorer 12, is given in Figure 16 [*Van Allen*, 1964]. The figure shows a large asymmetry between the day and night zones.

At the end of 1962 fluxes of electrons with energies $E > 70$ ev after crossing the outer radiation belt boundary were recorded in the night magnetosphere by means of charged particle traps carried by the Mars 1 probe at low geocentric distances ($2\ R_E < R < 4\ R_E$) but at high invariant geomagnetic latitudes ($\lambda \sim 65°$–$67°$) [*Gringauz et al.*, 1964; *Gringauz*, 1964]. This experiment confirmed the initial supposition contained in the hypothesis on the third radiation belt [*Gringauz et al.*, 1960*a*, *b*], that the inner boundary of fluxes of soft electrons lies along the outer boundary of the radiation belt, i.e., along magnetic shells.

Subsequently *Fritz and Gurnett* [1965] reported that from Injun 3 electron fluxes with energies of ~10 kev were observed outside the outer belt boundary at the same geomagnetic latitudes as from Mars 1. They observed the same fluxes that were detected by Luna 2 and Mars 1.

In 1964 on the Electron 2 satellite, fluxes of electrons (by a spherical elec-

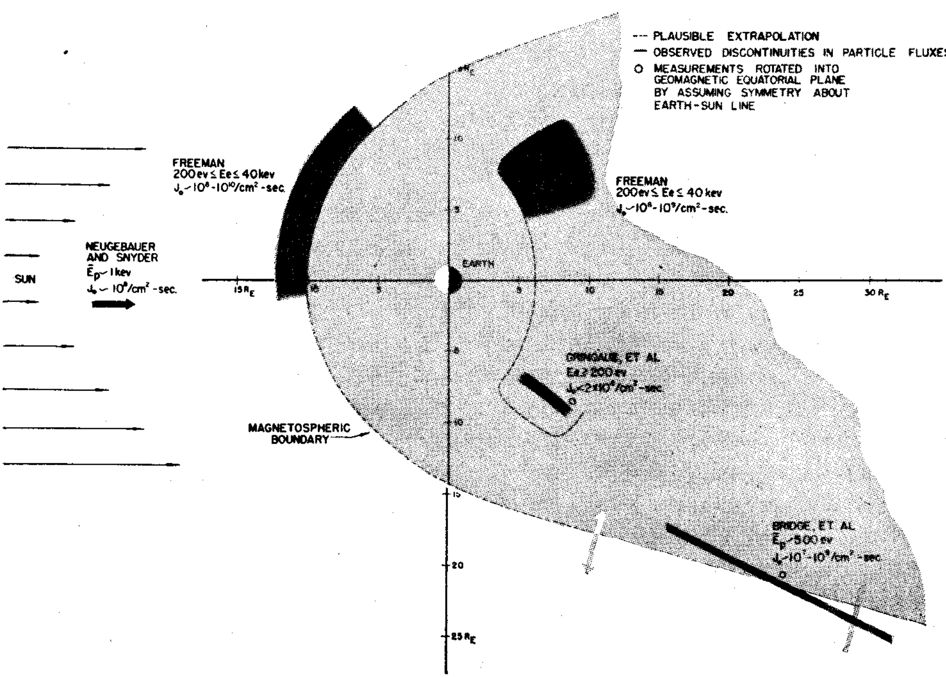

Fig. 16. The distribution of fluxes of electrons with energies 200 ev $\leq E \leq$ 40 kev in the equatorial plane [*Van Allen*, 1964].

trostatic analyzer) with energies from 100 ev to 10 kev were recorded outside the trapped radiation belt in the southern part of the magnetosphere at geomagnetic latitudes up to ~60° in the morning and near midnight [*Vernov et al.,* 1966]. The recorded fluxes reached the values $\sim 10^9$ cm^{-2} sec^{-1} kev^{-1} with energies of 0.2 kev and $\sim 5 \times 10^7$ cm^{-2} sec^{-1} kev^{-1} with energies of 10 kev. It was found that the range where fluxes of electrons with energies of ~1 kev were recorded is greater than that of electrons with energies of ~10 kev. A trend was observed toward the softening of the electron spectrum with increase of distance from the earth. The extent of the region and the magnitudes of the fluxes in it varied strongly with characteristic times of the order of a day and were positively correlated with geomagnetic activity.

Figure 12 shows some regions in which fluxes of electrons with energies $E > 100$ ev were detected beyond the outer radiation belt by means of charged particle traps on Electron 2.

Figure 17 gives the distribution of low-energy charged particle fluxes in circumterrestrial space, taking into account observational data obtained by different space vehicles, as was seen in 1965 [*Gringauz and Khokhlov,* 1965]. Projections in (*a*) the plane of the ecliptic and (*b*) the meridional plane are given in the solar ecliptical coordinate system. In comments on this figure it was pointed out that at that time (1965) there was not sufficient proof that the night and day regions of fluxes of electrons with energies $E < 40$ kev beyond the zone of trapped radiation are connected and form a common zone (see Figure 17*b*). However, the results of high-latitude measurements from Mars 1 and Electron 2 (Figure 17*b*) supported the idea that the night and day regions are interconnected at least at high latitudes, thus constituting a single region with a complicated configuration. On the other hand, it was not known that any spaceborne detectors of such electrons crossed the outer belt boundary without detecting low-energy electron fluxes beyond it. Since the outer boundary of the zone of trapped radiation is closed, it was supposed that the zones of the low-energy electron fluxes lying outside it also constitute a single region. This does not mean that the plasma fluxes in the day and night portions of this region are of the same origin and have identical properties.

On the basis of these assumptions, the authors of Figure 17 supposed that low-energy electron fluxes in the meridional plane lie in the region denoted by dots. Even now the lack of measurements in the high-latitude region of the magnetosphere precludes the opportunity of checking fully the validity of this supposition (Figure 17*b*). The results obtained on Electron 2 gave grounds for a preliminary conclusion [*Gringauz and Khokhlov,* 1965] on a connection between the intensity of the observed soft electron fluxes and the orientation of the earth's magnetic dipole axis with respect to the solar direction. Maximum electron fluxes were observed on the morning portions of the satellite orbits when the south magnetic pole is most inclined toward the sun, i.e., when conditions for the injection of the solar plasma into the magnetosphere from the magnetosheath through the south neutral point are most favorable. This conclusion was supported by the further processing of the above data by *Khokhlov* [1966] who also noted the existence of an east-west asymmetry in the distribution of

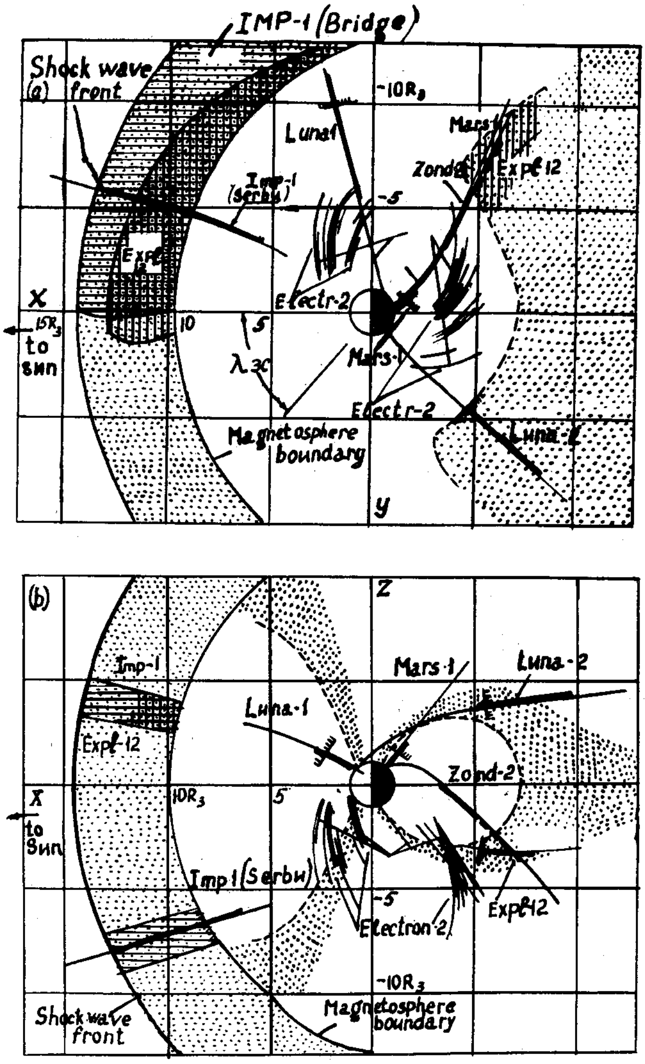

Fig. 17. The distribution of fluxes of low-energy charged particles in circumterrestrial space [*Gringauz and Khokhlov*, 1965]: (*a*) the ecliptic plane projection; (*b*) the meridian plane projection in the solar-ecliptic coordinate system. Sections of spacecraft trajectories where the fluxes of low-energy particles were registered are shown by thick solid and dashed lines; for the Electron 2 satellite, only these sections of orbits where soft electrons were observed (according to charged particle trap data) are shown. The outer boundary of the outer radiation belt is shown by the thin dashed curves and the sign in the form of a comb. A plausible position of the outermost charged particle zone is shown by dots.

soft electron fluxes. In the morning part of the magnetosphere, fluxes were more intense and were observed more frequently than in the evening part.

Among the major scientific results of the flight of the IMP 1 satellite are: confirmation of the observation that the magnetosphere is strongly extended in the antisolar direction (this was also suggested by earlier magnetic measurements from Explorer 10 [*Heppner et al.*, 1963] and Explorer 14 [*Cahill*, 1964]), and the discovery of the major new phenomenon, the magneto-neutral sheet in the night magnetosphere [*Ness*, 1965] (see Figure 1).

As was pointed out by *Axford et al.* [1965], the neutral sheet in the magnetospheric tail, to exist, must be inflated by enhanced plasma fluxes in order to balance the pressure of the magnetic fields on both sides of it (and oppositely directed). The magnetic field of the tail (outside the neutral sheet) measured by IMP 1 was ~17 gammas. In this connection *Ness* [1965] presented on a single graph (Figure 18) the results of observations of charged particle fluxes performed by different authors in the night magnetosphere; fluxes that would create the plasma pressure necessary for the existence of the neutral sheet. The range of magnitudes of fluxes and energies, in accordance with the data of magnetic measurements, is shown hatched. Since the results of our measurements were in this range, *Ness* [1965] assumed that electron fluxes, measured from Luna 2, are associated with the magneto-neutral sheet [see also *Gringauz and Khokhlov*, 1965]. Subsequently, in 1966 simultaneous magnetic and plasma measurements at geocentric distances of ~40 R_E were made when Pioneer 7 crossed the night magnetosphere. The measurements confirmed the correctness of the concept of a quasi-static magnetospheric tail, in which the sum of partial magnetic and plasma pressures is constant [*Lazarus et al.*, 1968]. This experiment is discussed in more detail below.

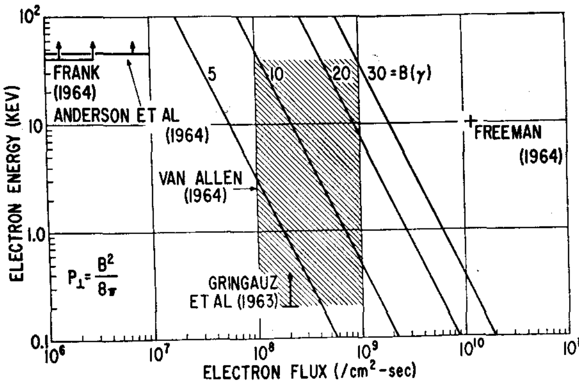

Fig. 18. Assumed pressure balance between vacuum magnetic fields in the magnetotail (without considering the existence of plasma) and a nonmagnetized electron gas for an idealized model of the neutral sheet. Superimposed are results of charged particle observations pertinent to the interpretation of the neutral sheet in the earth's magnetic tail [*Ness*, 1965].

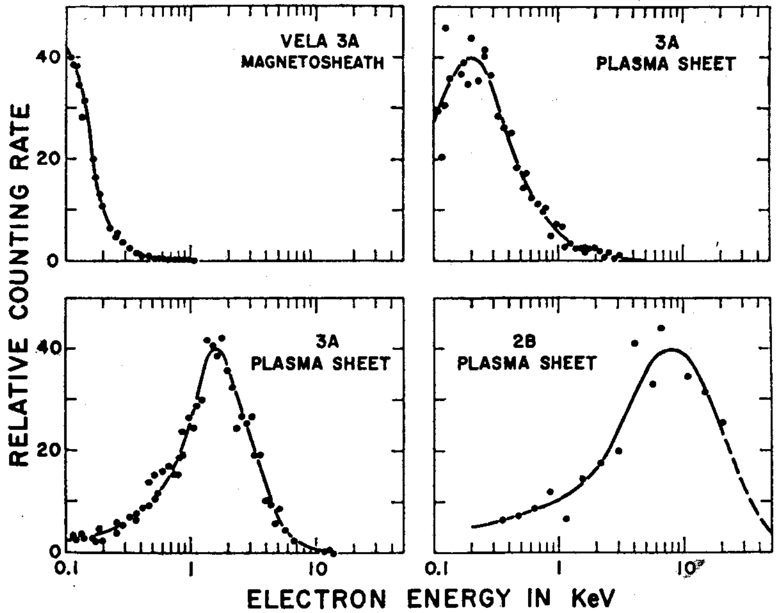

Fig. 19. Electron energy spectra measured by Vela satellites (*a*) in the magnetosheath behind the shock wave front and (*b, c,* and *d*) in the magnetotail plasma sheet [*Bame et al.*, 1967].

Beginning in 1964, detailed measurements of the energy spectra of electrons with energies of 350 ev $< E <$ 20 kev were performed in the cross sections of the magnetospheric tail at geocentric distances $R \sim 17\ R_E$ by means of spherical electrostatic analyzers of the Vela satellites [*Bame et al.*, 1967]. Figure 19 shows samples of the spectra obtained. Beside electrons, for the first time in this region positive ions were detected (mainly protons, apparently). Naturally their flux was much lower than the electron flux. According to the estimates of the experimenters, proton and electron densities are approximately equal and reach 1 cm^{-3}. Also, the shape of the proton energy spectra is quite similar to the shape of the electron energy spectra. The average energies of electrons lie in the range from 200 ev to 12 kev. Their fluxes are often isotropic; however, the magnitude of anisotropy reaches a factor of 2.

Detailed investigations of plasma with particle energies of ~200 ev to ~50 kev by means of high-sensitivity cylindrical electrostatic analyzers on OGO 3 (part of these investigations, relating to the radiation belts, is described in section 3) were also conducted in the magnetospheric tail at $8\ R_E < R < 20\ R_E$ [*Frank*, 1967*a*]. These investigations complemented well the measurements from the Vela satellites. The information on the position of the region of plasma fluxes in the magnetospheric tail, derived from the data of the electrostatic analyzers on Vela and OGO 3, can be summed up as follows: the magneto-neutral sheet always lies inside the plasma sheet. The plasma sheet greatly exceeds the magneto-neutral sheet in thickness. It was arbitrarily assumed that for Vela the plasma sheet boundary is defined by an electron flux of 6×10^7 cm^{-2} sec^{-1}. With such a definition, the thickness of the plasma sheet at $R \sim 17\ R_E$ was several R_E. On OGO 3 the electron fluxes were observed at $R = 19.5\ R_E$ at a distance of $\sim 12\ R_E$ above the neutral sheet (for the given measurement midway between the neutral sheet and the northern boundary of the magnetosphere).

Anderson [1965] and *Frank* [1965] reported on satellite observations in the magnetosphere tail. Sporadically appearing and vanishing 'islands' of electrons with $E > 45$ kev were observed. *Bame et al.* [1967] and *Frank* [1967*a*] concluded that these electrons belong to the tails of the energy spectra of low-energy electrons of the plasma sheet; emergence and disappearance of these electrons are accounted for by rapid heating (increase in the average energy) and cooling of electrons in the plasma sheet; i.e., by rapid variations of electron energy spectra. *Frank* [1967*a*] notes also rapid spatial and time variations of electron fluxes in the plasma sheet. The energy density near the electron flux 'peaks' does not decrease with increasing distance (when $R > 13\ R_E$) and nearly always amounts to 10^{-9} erg cm^{-3}, despite the fact that the average electron energies decrease with increasing distance. This was also inferred by *Vernov et al.* [1965*b*] from Electron 2 measurements.

The shift of energy spectra with the decrease toward high energies, accompanied by broadening of the spectra, suggests that the process of electron acceleration is effective at least in the region of the magnetic tail from 10 to 20 R_E; since the peak of the energy spectra shifts at 10 R_E by several kev, this acceleration may be ascribed to an electric field of ~ 5000 v/10 $R_E \approx 100$ mv km^{-1} [*Frank*, 1967*a*].

The above-mentioned value of the energy density of electrons in the plasma sheet in the magnetosphere tail shows that they considerably affect the magnetic field when $R > 8\ R_E$.

In simultaneous measurements by Pioneer 7 of the plasma and the magnetic field in the magnetosphere tail [*Lazarus et al.*, 1968], only electrons with energies of $E \leq 1.6$ kev were recorded. As is seen from measurements by *Frank* [1967*a*] at $R \sim 8\ R_E$, using the upper limit of electron energy of the plasma detector, only the less energetic electrons in this field can be observed. That is why the accurate determination of plasma pressure from the Pioneer 7 data is difficult. Nevertheless, the results of these simultaneous magnetic and plasma measurements are impressive and speak in favor of the quasi-static model of the magnetospheric tail. In this model the total pressure of the magnetic field and particles in the tail should be constant and equal to the total (dynamic, thermal, and magnetic) pressure of the solar plasma normal to the boundary surface of the magnetosphere. A simultaneous sharp decrease of magnetic pressure and increase of plasma pressure observed when Pioneer 7 entered the plasma sheet, and reverse changes when it left this sheet, as well as the phenomena observed when it entered the magnetically neutral sheet (the particle density nearly remained constant, and the average particle velocity considerably increased) also speak in favor of this quasi-static model.

Bame et al. [1967] concluded that the plasma sheet in the magnetosphere tail begins near the night boundary of the trapped radiation regions and that its orientation near its origin coincides with the geomagnetic equator plane. Far

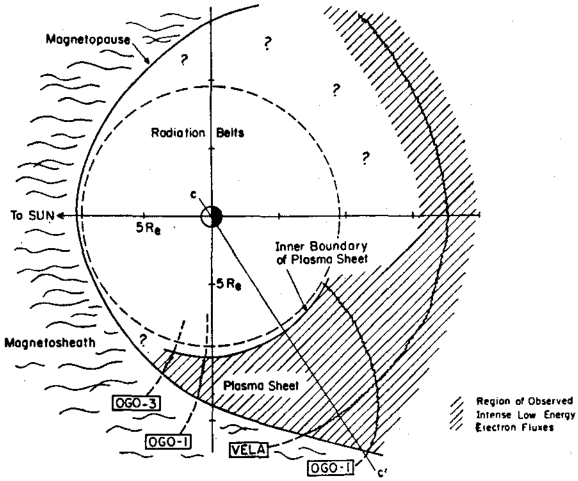

Fig. 20. Position of increased low energy fluxes ($E \leq 1.7$ kev) in the geomagnetic equatorial plane [*Vasyliunas*, 1968*b*].

away from the earth it corresponds to the direction of the solar wind. In Figure 1 the plasma sheet is shown this way [*Ness*, 1967]. The measurements of other authors do not contradict this supposition, and the results of *Vasyliunas* [1968*b*] obtained from OGO 1 and OGO 3 satellites directly confirm it. These results were obtained by means of the plasma detectors developed by MIT, which permit one to record the least energetic portion of the electrons of the plasma sheet in the magnetosphere tail ($\sim$100 ev $\leq E \leq$ 1650 ev). Figure 20 shows the distribution of low-energy electron fluxes in the equatorial plane of the magnetosphere plotted from Vela and OGO data. On the outer side, the magnetosphere boundary is a boundary of the zone of these plasma fluxes, which is determined from the appearance of considerable fluxes of electrons. On the inner side, there is a definite boundary close to the boundary of the zone of trapped radiation (and perhaps coinciding with it).

Figure 21 shows a similar distribution in the magnetospheric meridional

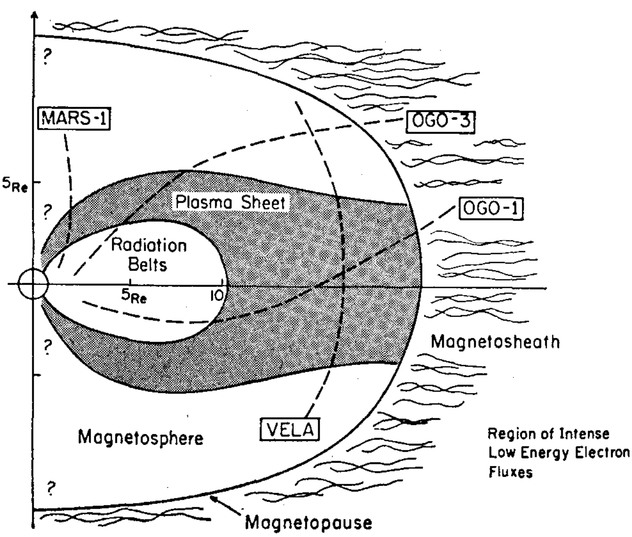

Fig. 21. Position of increased low-energy ($E \leq$ 1.7 kev) electron fluxes in a meridian cross section along the line *cc'* of Figure 20 [*Vasyliunas*, 1968*b*].

cross section corresponding to the late evening (the *cc′* line in Figure 20). To plot this distribution at high geomagnetic latitudes, data obtained from the Mars 1 probe have been used.

The observations described by Vasyliunas show that the fluxes of low-energy charged particles directly outside the outer radiation belt boundary are not a specific feature of only the magnetospheric nighttime region but also exist in its evening and possibly its daytime region. (It will be very interesting to hear at this symposium Vasyliunas's observations in the daytime region of the magnetosphere.) These results strongly support the concept of a single outermost belt of charged particles that surrounds the radiation belts, advanced earlier by the author [*Gringauz*, 1961*a*; *Gringauz and Khokhlov*, 1965]. However, the clearly defined inner boundary of the observed electron fluxes, with a discontinuity near the boundary of the outer radiation belt, is somewhat unexpected. This was not observed with other space vehicles (for example, Figures 12 and 17 show data of a charged particle trap that recorded electrons with energies > 100 ev on Electron 2). Apparently such a pronounced boundary was not observed by Frank on OGO 3; in any case, this has not been pointed out in his publications [*Frank*, 1967*a*, *b*]. Perhaps it is a specific feature of only those low-energy electrons ($E < 1.6$ kev) whose distribution is shown in Figures 19 and 20.

During magnetic storms of the bay type, *Vasyliunas* [1968*b*] observed the inner boundary of the soft electron zone to move inward (Figure 22). He pointed out a probable connection of this phenomenon with the motion of ion fluxes toward the earth during a magnetic storm [*Freeman and Maguire*, 1967].

To conclude this section, we discuss plasma measurements in the distant parts of the magnetosphere tail. The existence of the magnetosphere tail at distances $R < 31\ R_E$ was shown by IMP 1 measurements [*Ness et al.*, 1964]. The plasma in the magnetosphere tail differs from undisturbed interplanetary space in general and the transition region behind the front of a shock wave in particular, by a sharp decrease of the proton fluxes. From this circumstance, on the basis of the data of the charged particle trap on the moon's first satellite, Luna 10, launched in February 1966, it was concluded that the moon crosses the magnetosphere tail each month during four days, i.e., that its length is not less than $\sim 60\ R_E$ [*Gringauz et al.*, 1966*b*]. Inside the tail fluxes of $\sim 10^8\ \mathrm{cm^{-2}\ sec^{-1}}$ of electrons with energies > 70 ev (apparently belonging to the plasma sheet) were observed. Also in 1966 magnetic measurements from the earth satellite Explorer 33 showed that the length of the magnetospheric tail is not less than 510,000 km [*Ness et al.*, 1967*a*; Ness, 1967]; this confirmed the conclusion, drawn from low-energy plasma measurements on Luna 10, that the moon crosses the earth's magnetospheric tail.

Of paramount interest are plasma and magnetic measurements conducted on the Pioneer 7 probe at a distance of $\sim 1000\ R_E$ from the earth. So far only preliminary data of these measurements have been published.

Unlike plasma measurements in the magnetosphere tail on IMP 1 [*Wolfe et al.*, 1966*b*] and on Luna 10 [*Gringauz et al.*, 1966*b*], the measurements made by the Pioneer 7 electrostatic analyzer while crossing the region of space surrounding the sun-earth line at the above distance from the earth did not detect

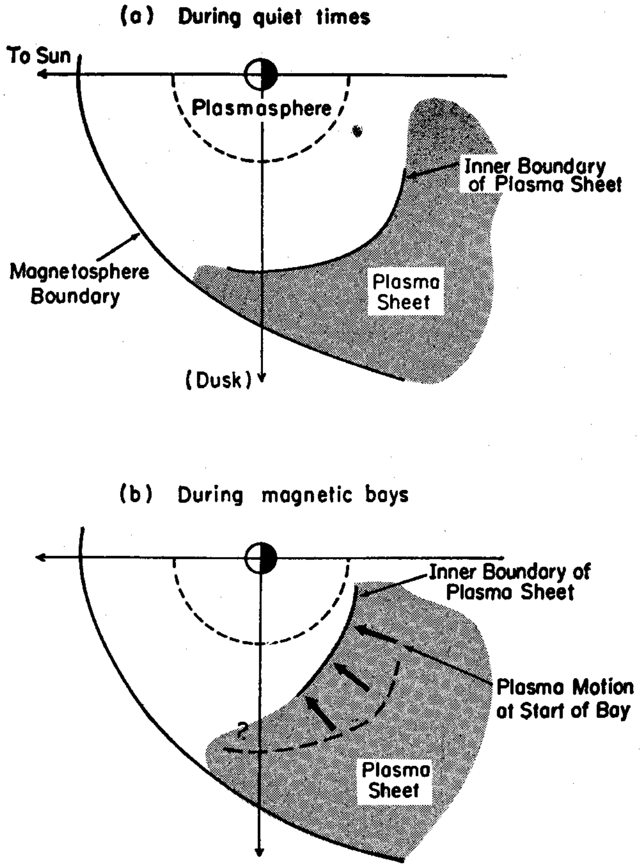

Fig. 22. The distribution of low-energy electrons ($E \leq$ 1.7 kev) in the evening side of the magnetosphere (*a*) during a magnetically quiet period and (*b*) during a disturbed period [*Vasyliunas*, 1968*b*].

a sharp decrease in solar plasma ion flux but showed significant distortions of the shapes of the ion energy spectra [*Wolfe et al.*, 1967]. The authors think that these distorted spectra may be accounted for by the fact that Pioneer 7 penetrated the turbulent zone outside the earth's magnetosphere or that at such great distances the solar wind diffuses inside the magnetosphere tail.

Ness et al. [1967*b*] described simultaneous magnetic-field measurements that also showed the differences of the observed field from the undisturbed interplanetary field, but the authors could draw no final conclusions as to the nature of these differences.

Comparing the magnetic data for Pioneer 7 at the $\sim$1000 R_E with data from Explorers 28 and 35 in circumterrestrial interplanetary space, *Fairfield* [1968] believes that Pioneer 7 observed the sweeping motions of the magnetosphere tail.

It seems to us, however, that additional comparisons of simultaneous plasma and magnetic measurements conducted on Pioneer 7 are needed for final conclusions.

5. CONCLUSION

Studies of low-energy plasma in different regions of the magnetosphere show that its characteristics, in particular its position, vary with geomagnetic activity. This refers both to the plasma in the outermost ionosphere, which apparently rotates with the earth, and to the plasma situated beyond the plasmapause.

At present, it is universally accepted that geomagnetic activity reflects changes of some or possibly several characteristics of the solar wind, although various authors differ on this point. The velocity of the solar wind [*Snyder et al.*, 1963], the direction of the interplanetary magnetic field [*Dessler and Walters*, 1964], the direction of the velocity vector of the solar wind [*Coleman*, 1967], etc., have been regarded as characteristics of the solar wind determining the magnitude of the K_p index. No matter who is nearest the truth, it is evident that the position of the plasmapause, the boundary of the zone of trapped energetic radiation, and the distribution and characteristics of the magnetospheric plasma with energies 100 ev $< E <$ 50 kev, as well as auroras and magnetic storms—all these phenomena, in the long run, are associated with processes taking place in the interplanetary medium. So far, simultaneous studies of measurements conducted in the earth's magnetosphere and outside it have led only to some rough empirical relations similar to those between the velocity of the solar wind and the K_p index [*Snyder et al.*, 1963] or between the electric field in the plane of the evening meridian and the velocity of the solar wind [*Vasyliunas*, 1968*a*].

There are grounds to believe that in the near future experiments will enable us to select the correct hypothesis from the abundance of existing ones as to a connection between the processes inside and outside the magnetosphere, or to develop a new theory if the existing ones do not justify themselves. Further measurements of low-energy plasma, together with magnetic data, will provide the basis for this theory.

I should like to point out some important but as yet unsolved experimental tasks connected with studies of low-energy magnetospheric plasma, and some related problems, which are reflected in this review insufficiently or not at all.

1. Despite considerable recent success in studying the low-energy magnetospheric plasma, both with thermal energies and energies from hundreds of electron volts to tens of kiloelectron volts (especially from OGO satellites), the studies of the distributions of low-energy charged particle fluxes in the magnetosphere and their variations are far from being completed. In the region $R > 2\ R_E$ at geomagnetic latitudes $> 45°$, the measurements conducted from the Mars 1 probe and from the Electron satellites remain unique up till now. This region, intermediate between the intensively studied zone of the magnetosphere at latitudes less than 45° and the region where auroras and associated phenomena take place, and which is characterized by high geomagnetic latitudes but low altitudes, should undoubtedly be investigated more intensively.

2. As mentioned in the previous section, the data obtained from Electron 2 testify in favor of the dependence of soft electron fluxes on the angle of inclination of the geomagnetic dipole and support the hypothesis that solar plasma is injected from the magnetosheath into the magnetosphere through neutral points of the magnetopause. To verify this, direct measurements of the magnitudes and directions of low-energy plasma fluxes in the direct proximity of the

neutral points would be very useful; for this, satellites with appropriate orbits are needed.

3. So far, the source of low-energy plasma in convective motion in the magnetosphere is uncertain. It may be the earth's ionosphere, or it may be the solar plasma penetrating into the magnetosphere through the open magnetic tail or the magnetopause. Apparently this plasma should be much colder in the first than in the second case. Therefore, it is very important to develop a reliable method of measuring the temperature of the plasma to within fractions of an electron volt when densities are of the order of 10^2 cm^{-3} (inside the outermost ionosphere) and of the order of 1 cm^{-3} (above the plasmapause).

4. In the present review we have not had space for the problem of electric fields in the magnetosphere, although they have been mentioned in connection with the detection (by the ATS 1 satellite) of low-energy plasma convection, and with the hardening of electron energy spectra outside the radiation belts in the night magnetosphere as one approaches the outer belt boundary (OGO 3, Electron 2). The motion of electrons with $E \leq 2$ kev during a magnetic storm, shown in Figure 22, is accounted for by the action of the electric field. Note that the recent review by *Obayashi and Nishida* [1968] is especially devoted to large-scale electric fields in the magnetosphere.

There is no doubt that the motion of charged particles in the magnetosphere (especially low-energy particles) is to a great extent determined by the electric field and, on the other hand, produces electric fields. Therefore, it is necessary to include direct measurements of electric fields in the program of future investigations of the low-energy plasma.

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