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The hot zone in the outer plasmasphere of the Earth

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Abstract—Ion temperature measurements, made within the plasmasphere on the Prognoz satellite, reveal that the L-shells are quasi-isothermal. The observed variations of temperature with both L-value and geomagnetic activity are described and discussed.

1. INTRODUCTION

To understand physical processes in the plasmasphere it is necessary to know its thermal structure (the temperature distribution of charged particles). The knowledge of the location of enhanced temperature regions allows us to localize heat sources. Values of ion and electron effective temperatures T_i and T_e are also needed to consider the pressure balance at the plasmapause. However, experimental determinations of these values are very scarce (and made up to the present only by two scientific groups—one in the U.S.S.R. and another in the USA). After the first estimation of the order of magnitude T_i ($T_i \sim 10{,}000$ K) from the spacecraft Luna-2 data, performed by GRINGAUZ *et al.* (1960), SERBU and MAIER (1966) conducted measurements from the IMP-2 satellite the results of which had caused some doubts (see BEZRUKIKH *et al.*, 1967). BEZRUKIKH *et al.* (1967) and GRINGAUZ *et al.* (1967) made estimations of T_i in the plasmasphere according to the data from the Electron-2 satellite. The last and the most complete published data on the ion temperature in the plasmasphere known to us were presented by SERBU and MAIER (1970) from measurements performed by the retarding potential method from OGO-5 satellite in the region near to the equatorial plane (the OGO-5 orbit inclination ~30°).

According to SERBU and MAIER (1970) the value of T_i increases gradually with the growth of the geocentrical distance R_E (which in case of OGO-5 is highly close to the MCILWAIN L-coordinate) for $\sum K_p \leqslant 11$ ($\sum K_p$—the sum of K_p—indices during the 24 hr) or oscillates for $19 \leqslant K_p \leqslant 27$ from the order of several hundreds of °K at $\mathscr{L} < 2$ to $T \geqslant 10^5$ K at $\mathscr{L} = 4$–4.5. SERBU and MAIER (1970) also observed an abrupt increase of T_i at the plasmapause for $\sum K_p > 15$.

In the present paper the results of determinations of T_i are given from the Prognoz satellite launched on 14 April 1972 into an orbit with initial parameters: perigee—200 km, apogee—940 km, inclination—65°. Owing to orbital peculiarities, during one revolution about the Earth the satellite crossed a given L-shell at different altitudes and this allows one to determine some features of the space distribution of n_i in the plasmasphere, not only in the equatorial plane but also far from it (GRINGAUZ and BEZRUKIKH, 1975).

2. TECHNIQUE OF MEASUREMENTS

Among wide-angle detectors of the low-energy plasma on the Prognoz satellite, two ion traps were installed with semispherical outer grids electrically connected to the satellite surface and flat collectors. One of the traps was placed at the illuminated part of the satellite and oriented to the Sun; another was at the shaded part and oriented in the antisolar direction (BEZRUKIKH *et al.*, 1974). The method used to determine T_i is based on the point that in the coordinate system connected to the satellite ion velocities are anisotropic and two ion traps oriented in a different way with reference to the satellite velocity vector (i.e. with reference to the incoming ion flux velocity) register different currents. The ratio of these currents depends on the anisotropy in the space of ion velocities and can be used for determination of T_i.

In the plasmasphere the ion trap collector current is

$$I_i = n_i G(V, T_i, l) \qquad (1)$$

where n_i—the ion density, G—a function obtained as a result of the integration of the product of the ion trap device function* by the proton velocity and by the ion distribution function in the velocity space. (It is supposed that the ion distribution function is Maxwellian and the contribution of heavier ions may be ignored in the plasmasphere),

V—the satellite velocity

l—the trap 'angle of attack' (the angle between the satellite velocity direction and the normal to the trap collector).

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* device function is the dependence of the collector current on the particle velocity and on the angle between the velocity and the normal to the trap collector.

The ratio of currents registered by two traps of different orientations is

$$\frac{I_{i1}}{I_{i2}}=\frac{G(V,T_i,l_1)}{G(V,T_i,l_2)} \tag{2}$$

(in the case when I_{i1} and I_{i2} measurements are made practically simultaneously). If V, l_1 and l_2 are known the only unknown value in (2) is T_i.

On the Prognoz satellite $l_2=180°-l_1$ and values of V and l were determined from the trajectory data. The measured values of the collector current of the trap illuminated by the Sun were corrected for the collector photo current. The value of the photocurrent was determined from the comparison of semi-spherical trap readings and those of the modulation trap (Faraday cup) which was also oriented to the Sun in the interplanetary space (the solar wind).

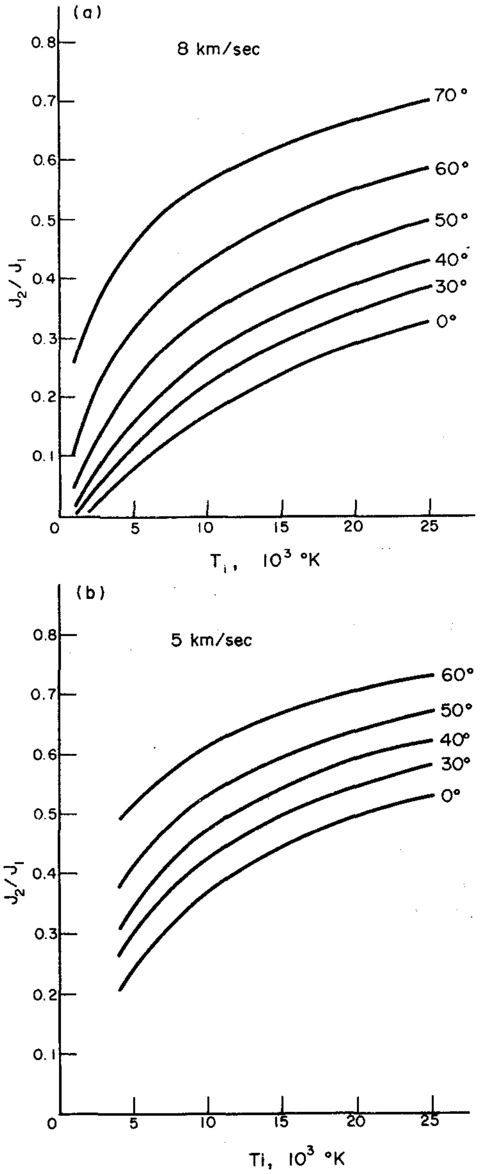

Fig. 1

In Fig. 1(a) the relation between I_{i1}/I_{i2} and T_i for different angles l are shown at the satellite velocity $V=8$ km/sec and in Fig. 1(b) at $V=5$ km/sec. From Fig. 1 one can see that the accuracy of the T_i determination from the known ratio I_{i1}/I_{i2} decreases with the growth of T_i and l_1. In the present paper the values of T_i were determined only for $T_i \lesssim 25{,}000$ K and in the interval of angles $l_1=0$–35° (in this case $l_2=180°$–155°) in further work we are going to determine T_i in the region $T_i>25{,}000$ K too, i.e. in the region, where errors of the T_i determination are larger.

The limits of the angle l allowed us to determine T_i only in the dayside plasmasphere and those of the ion thermal velocities T_i allowed determination only of the lower limit of possible values of T_i in some regions of the plasmasphere.

Curves shown in Fig. 1 are calculated under the assumption of zero electrical satellite potential φ_{sat} with reference to the surrounding media.

If one considers that errors of T_i measurements are determined by errors of measurements of I_{i1} and I_{i2} and inaccurate knowledge of l_1—values, one can show that in the period 8 May 1972–20 May 1972 (considered in the next section) when l_1 was less than 30° and $T_i<25{,}000^{\bullet}$ the relative error in the T_i determination was $\delta T_i/T_i \lesssim 10\%$ and in the period 17 June 1972–25 June 1972, when $\alpha \sim 30$–35°, $\delta T_i/T_i \lesssim 25\%$.

3. RESULTS OF MEASUREMENTS

In Fig. 2 the results of determinations of T_i are given during four successive passes of the Prognoz satellite near the Earth on 8, 12, 16 and 20 May 1972. At the left part of this figure the graphs of T_i and n_i are shown. On the abscissa axis heights and L-coordinates are given. The right part illustrates the satellite motion through L-shells with reference to the geomagnetic equatorial plane (the conditional meridonal plane is represented in which values of L and angles between the direction from the Earth's center to the satellite and the equatorial plane are equal to the corresponding parameters of the real motion in the three-dimensional space).

On the graphs at the left part are also shown: K_p—index at the moment of the start of measurements in the plasmasphere, K_{pm}—the maximum K_p—index for the preceding 24 hr, $(\sum K_p)_1$—the K_p

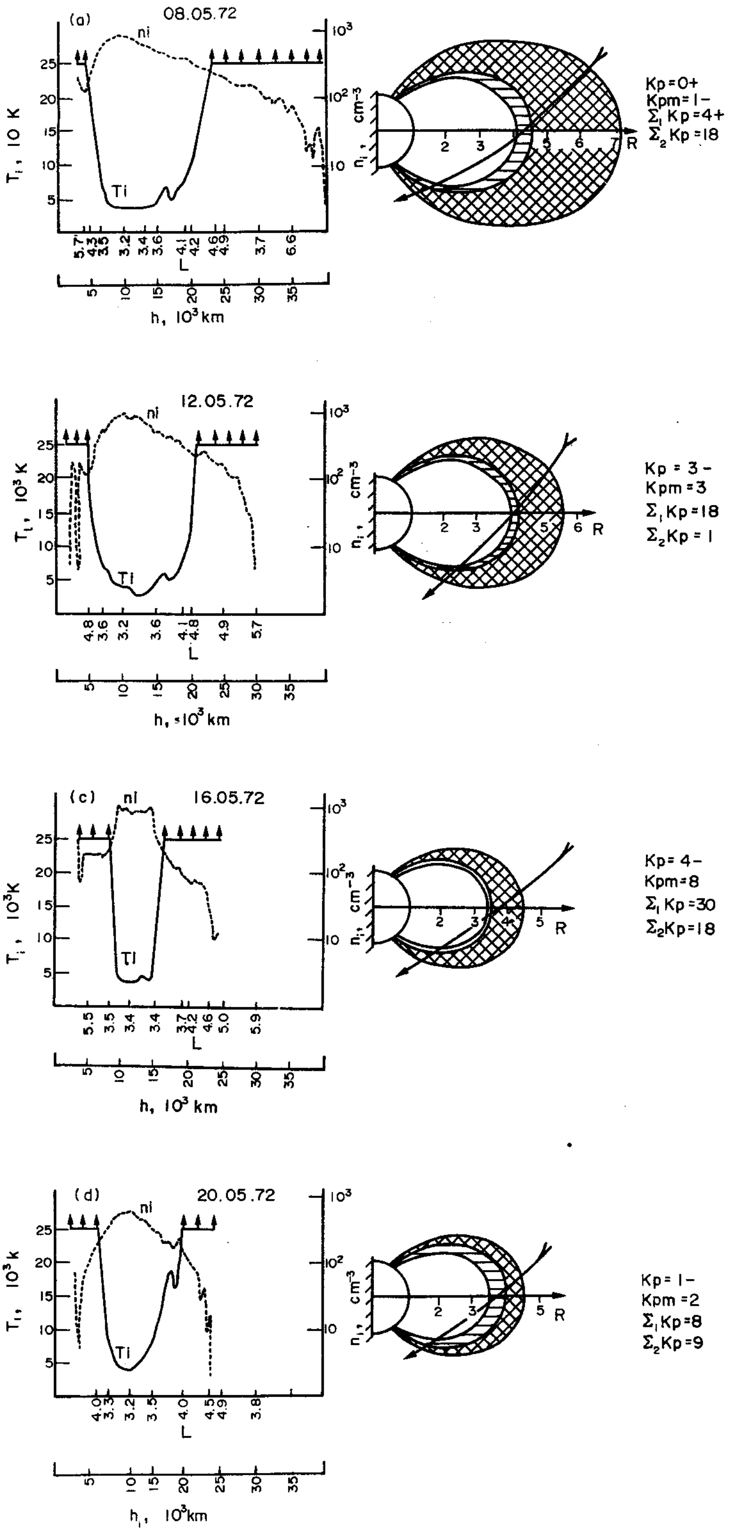
(a)
08.05.72
ni
Ti
T_i, 10 K
n_i, cm^{-3}
10^3
10^2
10
25
20
15
10
5
L
h, 10^3 km
Kp=0+
Kpm=1−
Σ_1 Kp=4+
Σ_2 Kp=18
R
12.05.72
T_i, 10^3 K
Kp = 3−
Kpm = 3
Σ_1 Kp = 18
Σ_2 Kp = 1
(c)
16.05.72
Kp= 4−
Kpm=8
Σ_1 Kp=30
Σ_2 Kp=18
(d)
20.05.72
Kp= 1−
Kpm =2
Σ_1 Kp=8
Σ_2 Kp=9

Fig. 2

sum for the preceding 24 hr and $(\sum K_p)_2$—the K_p sum for the following 24 hr.

T_i and n_i distributions in Fig. 2(a) are obtained after the prolonged and highly quiet period before the beginning of a weak disturbance. The L-coordinate of the dayside plasmapause is ~7.5. If we conditionally name the zone where $T_i \lesssim 8000$ K 'cold' zone and that where $T_i \gtrsim 25{,}000$ K 'hot' zone, one can note that the outer boundary of the cold zone corresponds to $L \sim 4$ and the inner boundary of the hot zone is placed on $L \sim 4.4$. In this case it is obvious that the value of T_i is determined not by the height h above the Earth's surface but by the value of L (with the increase of h from 4000 km to 8000 km and the decrease of L the value of T_i decreases; at heights $h \sim 8000$ to 17,000 km at $L < 3.7$ it keeps low values (4200°–6000°K) and only at altitudes >17000 km ($L \geqslant 3.7$) T_i begins to increase with the growth of h. In this case values of T_i at the same values of h but essentially different values of l are approximately the same. Careful consideration of measured values of T_i shows that at a given L-shell T_i is somewhat higher at low altitudes than at higher ones. This can be important for the localization of parts of field tubes in which the energy heating the plasma is dissipated. However, in the rough approximation used in this paper the L-shells are considered as quasi-isotemperature surfaces (we mean T_i).

In the case corresponding to Fig. 2, between the 'cold' and 'hot' zones of the plasmasphere, is the 'intermediate' zone where the value of T_i gradually increases with the growth of L.

The next measurements were performed on 12 May (Fig. 2b) during a weak disturbance ($K_p = 3$); the preceding period was also weakly disturbed ($\sum K_p = 18$). The outer boundary of the cold zone and the value of T_i in this zone and its position in L-coordinates and T_i in the intermediate zone show little change compared to Fig. 2(a), however, the plasmapause became considerably closer to the Earth (almost by 2 L-units) and the size of the hot zone decreased respectively.

The next measurement was conducted on 16 May during a strong geomagnetic storm beginning to become weaker (the commencement of the storm took place on 15 May). The value of T_i in the cold zone did not practically change and its size changed relatively not much (somewhat decreased), however, the growth of T_i with the increase of L at $L > 3.5$ was considerably accelerated and the intermediate zone almost disappeared—the hot zone approached the cold one. The plasmapause moved closer to the Earth as compared with its position in Fig. 2(b) (approximately by one L–unit). The results of measurements, which are given in Fig. 2(d) (on 20 May 1972) correspond to the recovery phase of the storm: K_p—indices are low but outer L–shells are not yet filled by the plasma and the L-coordinate of the plasmapause still keeps the value corresponding to the geomagnetic storm. However, the thermal structure of the plasmasphere has already changed—between the cold and hot zones the relatively wide intermediate region with the gradual increase of T_i was again formed.

Let us consider as an example three successive passes of the satellite through the dayside plasmasphere—on 17, 21 and 25 June 1972 (Fig. 3).

Figure 3 corresponds to the development phase of a great geomagnetic storm ($K_p = 7$, $(\sum K_p)_1 = 36$, $(\sum K_p)_2 = 55$). The plasmapause is located approximately at the L-shell on which the outer boundary of the cold zone ($L = 3.5$) was situated in Fig. 2. The part of the satellite orbit inside the plasmasphere is almost fully located between $L = 3.4$ and $L = 3$ and only in the range $h = 900$–1000 km, is displaced into the space where $L \lesssim 3$ (the right part of Fig. 3a). At the left part of Fig. 3(a) one can see that just in this interval of altitudes T_i decreases from the value $\geqslant 25{,}000$ K to 5000 K; the boundary between the cold and hot zones is sharp, the intermediate zone is practically absent.

Figure 3(b) corresponds to 21 June—the recovery phase ($K_p = 2_+$) in the beginning of a weak geomagnetic disturbance. The outer boundary of the cold zone has moved away from the Earth ($L = 3.6$) and the inner boundary of the hot zone is less sharp (the narrow intermediate zone appeared with the gradual increase of T_i).

The data in Fig. 3(b) correspond to 25 June a more prolonged quiet (weakly disturbed) period. The cold zone here is wider than in preceding cases (L-coordinate of the outer boundary $L = 4.2$) and there is a marked intermediate zone at $4.2 < L < 5$. The hot zone is placed in the outermost part of the plasmasphere ($L > 5$).

4. DISCUSSION

As mentioned above, the measurements show that from the point of view of the ion temperature each L-shell, to a rough approximation, can be considered as a quasi-isotemperature one. Therefore all the data on T_i including those obtained at high geomagnetic latitudes (on high L-shells) one can apparently reduce to the geomagnetic equatorial plane along field tubes and compare with the $T_i(L)$

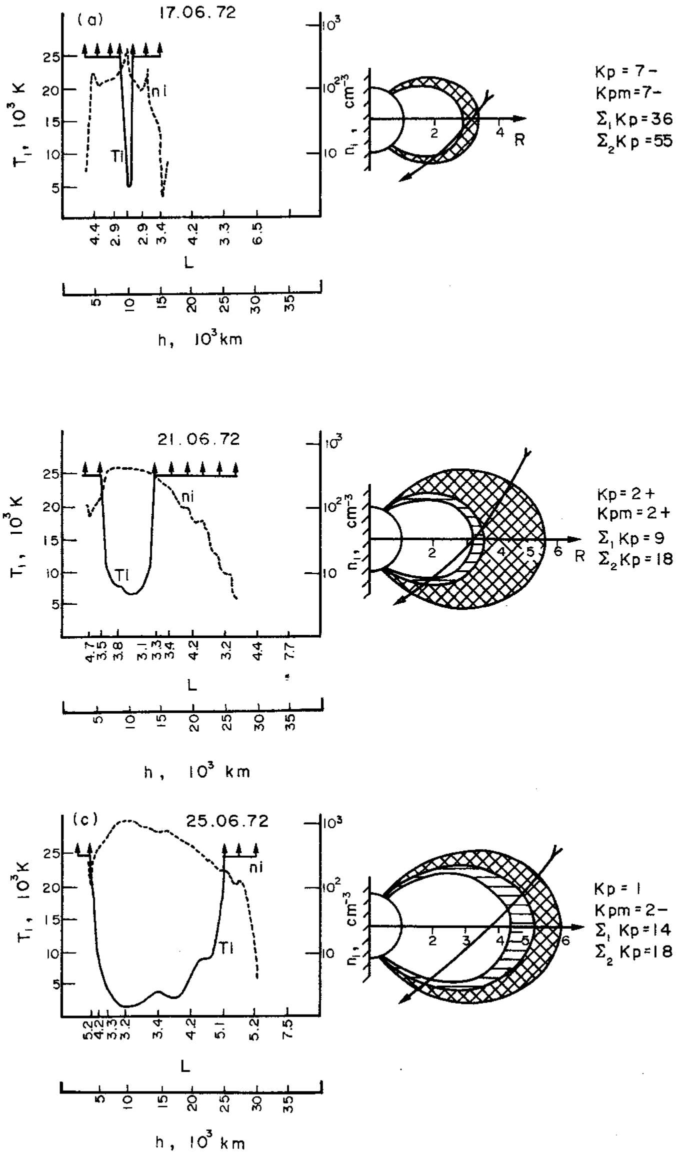

Fig. 3

distributions obtained by Serbu and Maier 1970 by means of the OGO-5 satellite near the equatorial plane. Such a comparison shows that between the data on T_i obtained from OGO-5 and those from Prognoz there are some differences but these are not very large.

One marked difference refers to the inner plasmasphere ($L \leq 3$) where the plasma is retained even during strong geomagnetic disturbances. According to the data from the Prognoz satellite in this region ('cold' zone) the value of T_i is always $\lesssim$8000 K. From the data by Serbu and Maier (1970) T_i in this zone is often higher and reaches in a number of cases several times 10^4 K. However, it should be borne in mind that the data of Serbu and Maier (1970) refer to 1968 (the period near the solar activity maximum) whereas the data from the Prognoz satellite refer to 1972 when the solar activity was considerably less. It is not excluded that T_i in the plasmasphere depends on the solar activity.

According to Serbu and Maier (1970) at $L >$ 3 T_i increases with the growth of K_p; sometimes this increase is sharp or oscillating (at $\sum K_p > 19$) and sometimes gradual (at $\sum K_p < 11$). Since in this paper the upper limit of measurement of T_i was 25,000 K it is impossible to perform a comparison of T_i at $L>3$ obtained from OGO-5 and from Prognoz but one can see that there is a qualitative coincidence of the two sets of results obtained in this region. However, according to OGO-5 data at $L>3$ oscillations of T_i were observed with increasing L, during which T_i sometimes became less than 10,000 K. There were no such decreases of T_i at $L>3$ in the Prognoz data.

Let us note that in cases when the 'intermediate' zone is absent, i.e. the cold zone has a sharp outer boundary (and the hot zone has a sharp inner boundary respectively (Figs. 2a and 3a, b), at this boundary no essential peculiarities in the n_i distribution were observed. This confirms the point that the cooling of ions due to Coulomb interactions at heights above 4000 km have no any essential influence upon the ion temperature in the plasmasphere.

Although in the described experiments the effective electron temperature T_e was not determined one can suppose that in the zone with high values of T_i the value of T_e is also high. As it is known (see, for example, the review by REES and ROBLE (1970)) in the subauroral upper atmosphere zones, onto which the plasmapause is approximately projected along L-shells, stable red arcs are observed and the existence of them can be explained by the increase of T_i. It is possible that the hot zone under consideration in the outer plasmasphere is the source of the increases of T_e.

To explain the origin of stable red arcs the mechanism of the heating of electrons, from which the stable arcs arise, is connected to the interaction of the ring current with the plasmasphere expansion in the recovery phase of a magnetospheric storm (CORNWALL *et al.* 1971. However, as one can see from Fig. 3(a), the inner boundary of the hot zone moves closer to the Earth in the development phase of the storm when the plasmasphere is not expanded but its size decreases. Therefore if the hot zone of the plasmasphere is the result of the interaction of the ring current with the distant plasmasphere, should we consider not only the intrusion of the cold plasma into the zone of existence of ring current particles during the expanding of the plasmasphere in the recovery phase of a storm but also the intrusion of these particles into the plasmasphere in the development phase of a storm (with corresponding simultaneous processes of the particle-wave interaction).

A possible mechanism of the heating of the plasmaspheric electrons during the interaction of the ring current with the plasmasphere was proposed by CORNWALL *et al.* (1970); the mechanism of the ion heating was proposed by GALEEV (1975).

SERBU and MAIER (1970) suggested that high values of T_i near the plasmapause are explained by the point that ions in this zone are temporarily captured into the magnetic trap by particles with energy $E>5$ ev belonging to the tail of the ionospheric ion Maxwellian distribution. SERBU and MAIER (1970) note that charged particles with $E<0.5$ ev due to the Coulomb scattering get into the loss cone during the first bounce whereas particles with $E=5$ eV can do 40 and more bounces. Just this process can support the predomination of protons with a relatively high energy at large values of L and, consequently, the high effective ion temperature.

However it should be noted that this mechanism does not give a key to the understanding of the hot plasma in the outer plasmasphere dynamics and does not explain causes of the existence of the highly sharp boundary of the hot zone observed in some cases from the Prognoz satellite.

5. CONCLUSION

Preliminary results of the ion temperature determination along parts of the Prognoz satellite orbit placed in the dayside plasmasphere showed that the value of T_i in the plasmasphere mainly depends not on the height h above the Earth's surface but on the L-coordinate. At essentially different values of h but at the same L, measured values of T_i are close, i.e. L-shells can be considered as quasi-isotemperature ones in the case of ions.

In the 'inner' plasmasphere (in which the plasma is not lost even during strongest magnetospheric storms) the value of T_i is stable and it does not exceed 8000 K, independently of the geomagnetic storm intensity. This zone of the plasmasphere can be considered as a 'cold' one.

In the outer plasmasphere the hot zone with $T_i>25{,}000°$ always occurs adjacent to the plasmapause. During strong magnetospheric storms the inner boundary of this zone is very sharp and is adjacent to the 'cold' zone.

During prolonged magneto-quiet periods the cold zone can extend to $L \sim 4$ and between the 'cold' and 'hot' zones the intermediate region can arise and its width in the equatorial plane can reach one Earth's radius (one L-unit). In this intermediate zone the value of T_i gradually increases from $T_i \sim 8000$ K to $T_i>25{,}000$ K with the increase of L.

Earlier, in connection with the theory of the stable red arc formation, some possibilities were considered of the interaction of the expanding plasmasphere (in the recovery phase of the magnetic storm) with the developed ring current, which can lead to the heating of outer plasmasphere. The results of the determination of T_i from the Prognoz data give evidence in favour of the point that the heating of the outer plasmasphere takes place also during the decrease of the plasmospheric size in the process of the ring current formation in the magnetic storm development phase (since the inner boundary of the hot zone approaches the Earth, i.e. the cold part of the plasmasphere is heated). One can expect that in this case stable ed arcs also arise.

The Prognoz data processing is continuing. In future we are going to estimate the value of T_i in the sections of the same L-shell.

REFERENCES

BEZRUKIKH V. V., BREUS T. K. and GRINGAUZ K. I.	1967	*Kosmicheskie issledovaniya*, **5,** 798.
BEZRUKIKH V. V., BELGASHIN A. P., VOLKOV G. I., GRINGAUZ K. I., DENSCHIKOVA L. I., ZASTENKER G. N., KAPTSOV V. G., KOPYLOV V. F., MOKROV V. S., MUSATOV L. SA., POZDNOV JU. N., REMIZOV A. P. and KHOKHLOV M. Z.	1974	*Geom. i aeron.* **I4,** 399.
CORNWALL J. M., CORONITI F. V. and THORNE R. M.	1971	*J. geophys. Res.* **76,** 4426.
GRINGAUZ K. I., BEZRUKIKH V. V.	1976	*J. atmos. terr. Phys.* **38,** 1071.
GRINGAUZ K. I., BEZRUKIKH V. V., OZEROV V. D. and RYBCHISKY R. E.	1960	*Doklady AN SSSR* **I3I,** I30I.
GRINGAUZ K. I., BEZRUKIKH V. V. and BREUS T. K.	1967	*Kosmicheskie issledovaniya*, **5,** 245.
SERBU G. P. and E. J. R. MAIER	1967	*J. geophys. Res.* **71,** 3755.
SERBU G. P. and MAIER E. J. R.	1970	*J. geophys. res.* **75,** 6103.
REES M. H. and ROBLE R. G.	1975	*Res. Geophys. and Space Phys,* **13,** 201.
GALEEV A. A.	1975	*Plasma turbulence in the magnetosphere with special regard to plasma heating.* Paper presented to Nobel symposium on hot plasma in the magnetosphere, Kiruna, 1975 April.