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EFFECT OF SOLAR ACTIVITY AND SOLAR WIND PARAMETERS ON PLASMA TEMPERATURE AND DENSITY IN EARTH'S PLASMASPHERE

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Abstract. Measurements from the Interball-1 and Magion-5 satellites of the Interball mission in 1995-2001 have been used to analyze the dependence of the equatorial plasmasphere characteristics on magnetic local time, as well as on solar activity, dynamic pressure, and solar wind density. The proton density at solar minimum is on average higher than at solar maximum, which is probably due to changes in plasma mass composition in the plasmasphere at solar maximum. The daytime and nighttime proton temperatures increase with increasing solar extreme ultraviolet flux, at least in the years of solar maximum. The plasmaspheric plasma density and thermal pressure rise with increasing dynamic pressure and/or density of the undisturbed solar wind, which might be associated with restructuring of the convective electric field in the magnetosphere.

Keywords: cold plasma, density, temperature, magnetic local time, solar activity, geomagnetic activity, solar wind pressure.

INTRODUCTION

Most studies analyzing the solar wind (SW) effect on the inner magnetosphere are limited to considering the outer boundary of the cold plasma region — the plasmapause.

Plasma density variations in the plasmasphere on different L shells (L is the McIlwain parameter, the distance in the magnetic equator plane to the geomagnetic field line in Earth radii R_E) during the day, year, and solar cycle were first discussed in [Park et al., 1978] based on whistler data. The plasma density, determined from the frequency and time of whistler propagation, refers to the equatorial plane of the plasmasphere. The large statistical data obtained from a ground station in California (~110° W) shows annual density variations. The plasma density on the magnetic shell $L\approx2.5$ in December was ~1.5 times higher than in June. As solar activity decreased in the period from 1957 to 1964, the plasma density also decreased. Moreover, Park et al. [1978] with reference to previous studies emphasized that plasma dynamics in the inner plasmasphere at $L<\sim3$ differs from plasma dynamics in the outer plasmasphere. Plasma distribution in the inner plasmasphere is little affected by geomagnetic activity and is close to the equilibrium saturation level, when downward plasma flows from the plasmasphere at night are balanced by flows from the ionosphere during the day.

Carpenter and Andersen [1992] have examined not only a change in the location of the plasmapause, but also the dynamics of the cold plasma density in the plasmasphere near the equatorial plane at $2<L<8$ under various conditions. Using data from ISEE wave experiments and ground-based whistler research data, an empirical formula have been derived for calculating the maximum electron density N_{eq}, recorded under prolonged quiet geomagnetic conditions,

$$\begin{aligned}\lg\left(N_{eq}(L,d,R)\right) &= -0.3145L+3.9043+\\ &+0.15\cos\left[2\pi(d+9)/365\right]\exp\left[-(L-2)/1.5\right]-\\ &-0.5\cos\left[4\pi(d+9)/365\right]\exp\left[-(L-2)/1.5\right]+\\ &+(0.00127R-0.0635)\exp\left[-(L-2)/1.5\right],\end{aligned} \quad (1)$$

where d is the ordinal number of the day in the year; R is the sunspot number averaged over 13 months. In (1), the first two terms are the main ones describing a decrease in plasma density with distance away from Earth, but the authors also take into account the increase in cold plasma density with increasing solar activity, annual (or seasonal) variations with maximum density in December, and semi-annual variations with maximum density at the equinox [Carpenter, 1962]. However, Formula (1) does not contain a dependence on the magnetic local time (MLT). To identify such a dependence, there was insufficient data obtained in the inner plasmasphere during long quiet periods.

Later, it was found that annual variations in the density of plasmaspheric plasma are not always accompanied by the observation of the December maximum. The plasma density in the plasmasphere in June may be higher than in winter. This depends on the geographic longitude of the observation area [Menk et al., 2012; Chugunin et al., 2017; Kim et al., 2018]. Yasyukevich et al. [2019] have analyzed total electron content variations in the plasmasphere (*PEC*) over Irkutsk (52°17' N, 104°18' E) during the daytime and at night for several years (2010–2013). The authors showed that in this region *PEC* values are higher in summer than in winter; increased *PEC* values were also recorded during equinoxes. Correlation with geomagnetic and solar activity indices was observed only for daytime *PEC*.

The direct dependence of the plasmaspheric plasma density on solar activity has not been confirmed either. Shim et al. [2017], indeed, point to a slight increase in *PEC* by 10–30 % at 1336–20200 km with an increase in solar activity, but at the same time they observe a decrease in the electron content near the equatorial plane with an increase in geomagnetic activity during solar maxima. Richards et al. [2000] analyze seasonal plasma density variations in the plasmasphere and indicate that the electron density anticorrelates with both geomagnetic and solar activity due to changes in the neutral hydrogen density of the ionosphere.

Variations in the inner plasmasphere parameters should be closely linked to variations in the upper ionosphere parameters. Plasma density and temperature variations with a period of 27 days (the synodic rotation period of sunspots is 27.2753 days) in the upper ionosphere according to DMSP data have been examined by Rich et al. [2003]. At solar maximum in the dusk sector, the density periodically changes by 40–50 %; and the temperature, by 5–10 %. The 27-day variations in the upper ionosphere parameters were detected at all latitudes below the polar oval. These latitudes correspond to magnetic shells of the plasmasphere. The authors naturally attribute the presence of such variations in the upper ionosphere parameters to variations in the ionizing ultraviolet radiation from the Sun. At the same time, in the lower ionospheric regions in the E or F layers, such variations in plasma parameters are subtle in the equatorial plane [Lee et al., 2012]. According to [Rich et al., 2003; Lee et al., 2012], at low altitudes the distribution of ionospheric plasma is subject to other strong dynamic processes that mask 27-day variations. Rich with co-authors suggested that similar variations in the parameters should exist in the plasmasphere.

The existence of ~27-day plasma density variations in the plasmasphere was reported only when analyzing data obtained by the Van Allen Probes satellites at L>4.5 [Thaller et al., 2019]. The authors found no correlation between the plasma density in the outer plasmasphere and the extreme UV flux (EUV, Extreme Ultra Violet) and attributed the observed variations to the effect of the convection electric field in the magnetosphere, i.e. to the processes of emptying and filling the plasmasphere. For the outer plasmasphere, this explanation seems to be quite reasonable.

The direct effect of SW on the plasma density in the plasmasphere was apparently first considered by Kotova et al. [Kotova et al., 2002a, b]. Data obtained by Interball-1 in July–October 1999 in the dusk (15–22 MLT) and dawn (02–10 MLT) sectors on the outer L shells of the plasmasphere (L~3.5) indicated that the plasma density in the plasmasphere increases with increasing SW dynamic (ram) pressure. A delay between measurements of SW and plasma in the plasmasphere was no longer than 6 hrs.

Jakowski and Hoque [2018] observe that the empirical model of plasmasphere density constructed for L<3 indicates that the cold plasma density in the inner plasmasphere is higher on the dayside than on the nightside at the same initial density values at a height of 1000 km. The authors attribute this fact to the compression of the dayside magnetosphere since it is flowed around by the SW stream.

From measurements of SW parameters (density, dynamic pressure, electric field, and the geomagnetic activity index K_p), a numerical model of the plasmasphere with machine learning has been built which can predict characteristics of this region of the magnetosphere 1–2 days in advance [Bianco et al., 2023]. This suggests that the direct effect of SW on the inner magnetosphere is significant and requires careful analysis.

Almost all studies in Earth's plasmasphere are based on measurements of the plasma density, most often the electron density, which can be obtained from various wave experiments that involve examining the low-frequency radiation in the magnetosphere. Direct measurements of plasmaspheric parameters are very rare, but only in such experiments it is possible to determine the thermal plasma temperature and energy.

In this paper, using measurements from the Interball-1 spacecraft and the Czech subsatellite Magion-5 of the Interball mission for 1995–2001, we first analyze the dependence of the equatorial plasmasphere characteristics on the distance to Earth (L) and on the magnetic local time, which will reduce the influence of these factors on the search for other causes of plasmaspheric plasma density and temperature variations. Then, we examine the effect of solar activity and SW parameters on the cold proton density and temperature in Earth's plasmasphere.

1. EXPERIMENTAL DATA

This work is based on data acquired by the retarding potential wide-angle cold plasma analyzer PL-48 (Faraday cup) installed on the Interball satellites.

Interball-1 was launched in August 1995 into orbit with an apogee of ~200000 km, a perigee of ~500 km, an inclination of 63.8°, and an orbital period of ~90 hrs. It crossed the plasmasphere ~1 time every 4 days at solar minimum of cycle 23 in 1995–1997 and at solar maximum of the cycle in 1999–2000. In the initial period after launch, the satellite reached the L shell closest to Earth L_{min}~1.4. Later, as a result of the evolution of the orbit, its perigee rose and in 1997–1998 during the ascending phase of the solar cycle the satellite only occasionally entered the plasmasphere and recorded cold plasma; from 1999 until the end of its active operation, the perigee of the orbit decreased. In each Interball-1 orbit, minimum L values were observed near the magnetic equator, and this made it possible to analyze the dynamics of cold plasma parameters in the magnetic equator plane as a function of L, eliminating the latitude dependence [Kotova, Bezrukikh, 2022]. Energy spectra of ions (0–25 eV) were measured for 2 s at different intervals from 30 s to 5 min depending on the telemetry mode.

Magion-5, whose data was also used for the analysis, was launched in August 1996 together with the main spacecraft Interball-2 into an orbit with an inclination of ~65°, a perigee of ~1.2 R_E, and an apogee of ~4 R_E. Because of various technical problems, the PL-48 device data was obtained only from August 1999 to July 2001, when the spacecraft ceased its active operation. Measurements from this spacecraft were carried out with a sufficiently high time resolution; the energy spectrum of thermal protons was measured for 0.4 s in cadence of ~8 s. The orbital period of Magion-5 was ~6 hrs, i.e. it crossed the plasmasphere four times a day. However, for various reasons, most of the data was obtained per day only on one inbound branch of the orbit; occasionally, there is data from two consecutive orbits of the satellite, but also only when it enters the plasmasphere.

Both SC were stabilized by rotating with a two-minute period around an axis directed at the Sun. When calculating plasma parameters from measured spectra, it was assumed that in the thermal region the particles are distributed by energy according to the Maxwellian law, taking into account partial shielding by the potential of the satellite with due regard to the rate of corotation of plasma with Earth and the spacecraft velocity [Kotova et al., 2014].

Databases obtained during periods of weak and moderate geomagnetic activity near the plane of Earth's magnetic equator were created to analyze the dependences of plasmaspheric plasma parameters on solar activity and SW characteristics. This excludes the influence of the magnetic latitude dependence on the data [Artemyev et al., 2014]. Interball-1 data was collected at 1.2<L<5; and Magion-5 data, at 2.5<L<3.5. Figure 1 illustrates radial distributions of the proton density (*a*) and temperature (*b*) in the plasmasphere in the equatorial plane according to Interball-1 data [Kotova, Bezrukikh, 2022]. The data is classified by local time; for Interball-1, it turned out that daytime crossings occurred from September to January; and nighttime crossings, from March to July. It is apparent that at L>3.5 the dependences, which approximate the density distribution, and the point fields coincide; yet in the inner plasmasphere the density during the day is about 1.5 times higher than at night. The general, regardless of local time and season, equatorial distribution of density N was approximated by the dependence

$$N = 6500\,L^{-2.7}. \qquad (2)$$

Kotova and Bezrukikh [2022] have shown that (2) fits well with other empirical relations derived in a smaller range of distances from Earth. By scaling $N \sim L^{-2.7}$, the data from the two satellites was reduced to L=3. This procedure mitigates the effect of the plasmaspheric density dependence on the distance from Earth. The local time dependence is discussed in more detail in the next section. Similarly, the proton temperature T, measured on different L shells by Interball-1 and Magion-5 was reduced to L=3, using the expression $T \sim L^{0.4}$, although it can be seen from Figure 1, *b* that distributions of T have a much larger range of values and differ by 15–20 % day and night.

2. MAGNETIC LOCAL TIME DEPENDENCE OF PLASMA CHARACTERISTICS IN THE PLASMASPHERE

Figure 2 shows the magnetic local time dependence of the proton density (*a*) and temperature (*b*) calculated from Magion-5 data. All Magion-5 measurements were made during solar maxima of cycle 23 over the region 50° W – 60° E. Significant changes in the plasmaspheric plasma parameters are observed within 24 hours.

According to the data, the maximum density is observed in the vicinity of noon. At noon (12:00), the proton density exceeds the night density ~2–5 times (Figure 2, *a*). The maximum temperature was recorded at ~16:00 (Figure 2, *b*), which corresponds to the maximum in the diurnal variation of ion and electron temperatures in the ionosphere in the F layer and above [Lyashenko, 2005]. The diurnal behavior of ion density and temperature is seen to be independent of season: the apparent change in the parameters measured in May–July (red dots) near the summer solstice gradually transforms to a change in the parameters measured in winter (blue dots) near the winter solstice. We can also see a slight rise in temperature during early morning hours, which coincides with diurnal temperature variations in the ionosphere.

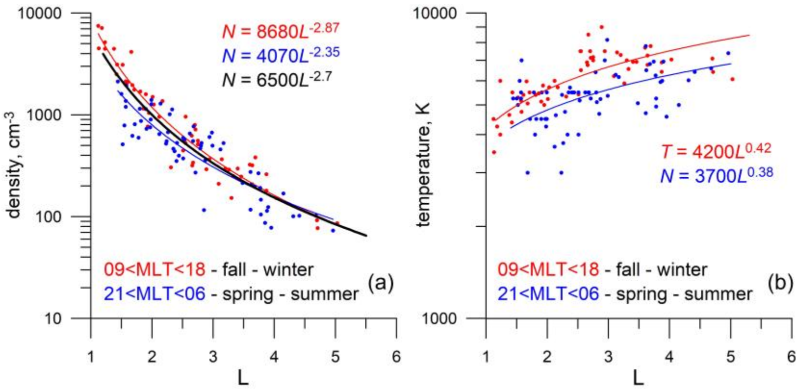

Figure 1. Proton density (*a*) and temperature (*b*) measured by Interball-1 in the plane of the magnetic equator of the plasmasphere for two MLT intervals (daytime hours 09:00–18:00 (red dots) and night hours 21:00–06:00 (blue dots)), as function of the distance to the center of Earth. The corresponding power-law approximations are highlighted in the same colors. The black curve in panel *a* indicates general approximation (2)

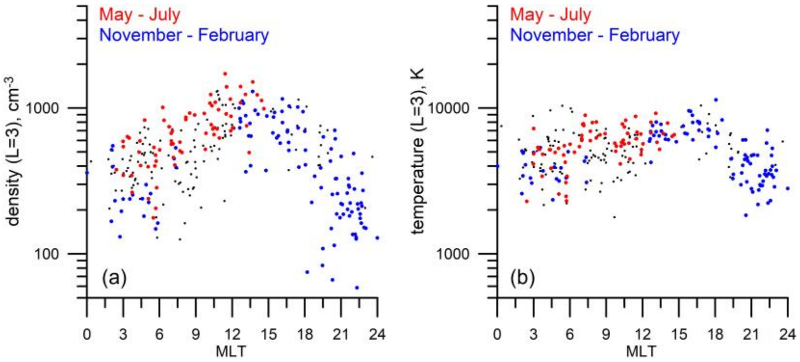

Figure 2. Proton density (*a*) and temperature (*b*) measured by Magion-5 in the plane of the magnetic equator of the plasmasphere as function of the magnetic local time. Black dots mark all measurements; red dots, measurements made in May–July near the summer solstice; and blue dots, parameters measured in winter near the winter solstice.

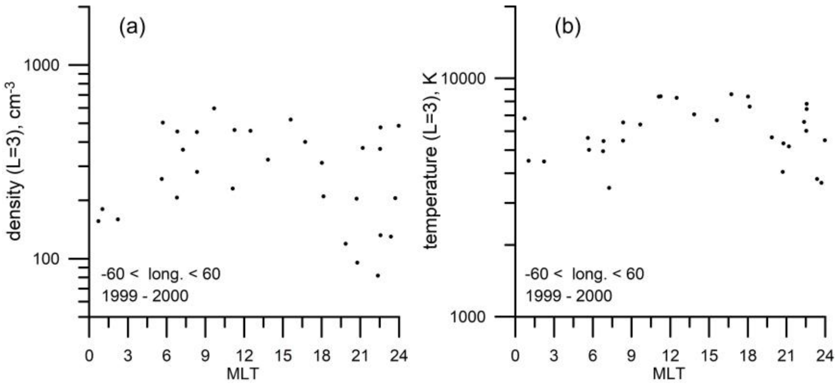

Figure 3. Magnetic local time dependences of the proton density (a) and temperature (b) measured by Interball-1 in the plane of the magnetic equator of the plasmasphere. The presented measurements were carried out in 1999–2000 in the range of geographic longitudes from –60° to 60°

Interball-1 data relates to the years of both low solar activity (1995–1997) and solar maximum (1999–2000). When presenting all the data depending on MLT, no daily change in the parameters is observed. Figure 3 illustrates variations in the proton density and temperature during the day, but measured only during solar maximum in the range 60° W — 60° E. Despite the small number of points, the diurnal behavior of the temperature and density is similar to that shown in Figure 2 according to Magion-5 data.

3. EFFECT OF SOLAR ACTIVITY ON PLASMASPHERIC PLASMA CHARACTERISTICS

As already mentioned, the Magion-5 measurements were carried out during solar maxima of cycle 23 when the parameters characterizing solar activity vary widely and this makes it possible to see the solar activity dependence of the proton density and temperature in the plasmasphere. Interball-1 measurements were made both during solar minimum (1995–1997) and solar maximum of the cycle, which allows us to compare the plasmaspheric plasma density and temperature in different periods.

Figure 4 plots the proton density (*a*, *b*) and temperature (*c*) in the plasmasphere, measured near the plane of the magnetic equator and normalized to L=3, as function of the sunspot number R_s (*a*) and the solar radio emission flux *F*10.7 (*b*, *c*).

The index *F*10.7 correlates well with the EUV solar flux. This flux is the main factor of ionospheric ionization from the E layer and higher [Chen et al., 2011]. Although *F*10.7 does not always correctly describe the EUV radiation flux, it is usually used to estimate its variations.

Interball-1 data (Figure 4, *a*, *b*) indicates that the proton density at solar minimum of the cycle (green dots) is on average higher than at solar maximum (purple dots). Any dependence of the proton density in the plasmasphere on these indices was failed to be identified from Magion-5 data at solar maximum when R_s changed from 40 to 350; and *F*10.7, from 120 to 325. However, both day and night proton temperatures are seen to increase with increasing solar activity (Figure 4, *c*).

4. 27-DAY AND ANNUAL VARIATIONS IN PLASMASPHERIC PARAMETERS

Figure 5 shows an attempt to detect ~27 day proton temperature and density variations in the plasmasphere. Vertical lines indicate official data on the beginning of Carrington cycles (~27.3 days) [https://www.astroleague.org/files/obsclubs/Carrington%20Rotation%20Start%20Dates.pdf]. The bottom panel depicts changes in *F* 10.7. The peak of this index in late March – early April 2001 was linked with strong X-class solar flares during this period.

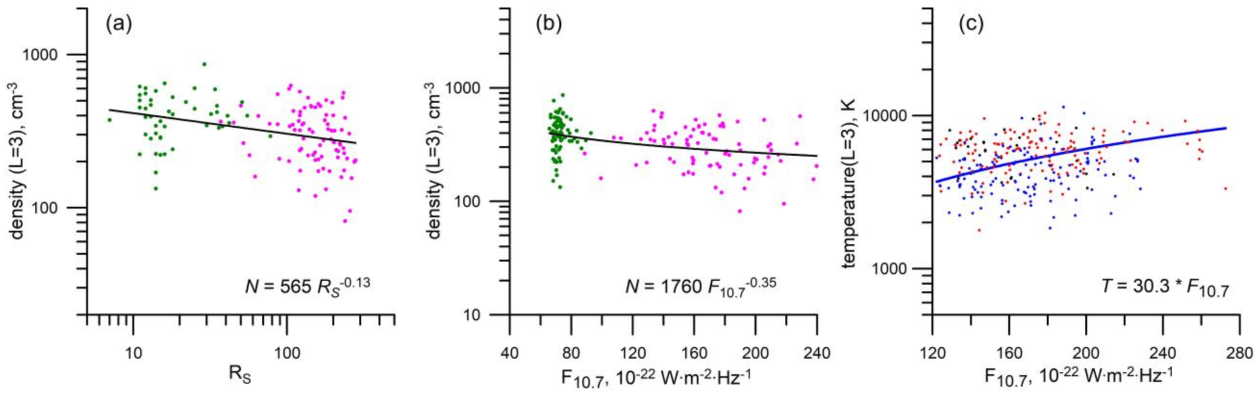

Figure 4. Proton density (*a*, *b*) and temperature (*c*), measured by Interball-1 (*a*, *b*) and Magion-5 (*c*) in the plane of the magnetic equator of the plasmasphere, as function of the solar activity indices R_s (*a*) and *F*10.7 (*b*, *c*). Measurements at solar minimum (1995–1997) are highlighted in green in the left panels (*a*, *b*); measurements at solar maximum (1999–2000), in purple. In the right panel (*c*), daytime measurements (06–18 MLT) are shown in red; and nighttime measurements (18–06 MLT), in blue

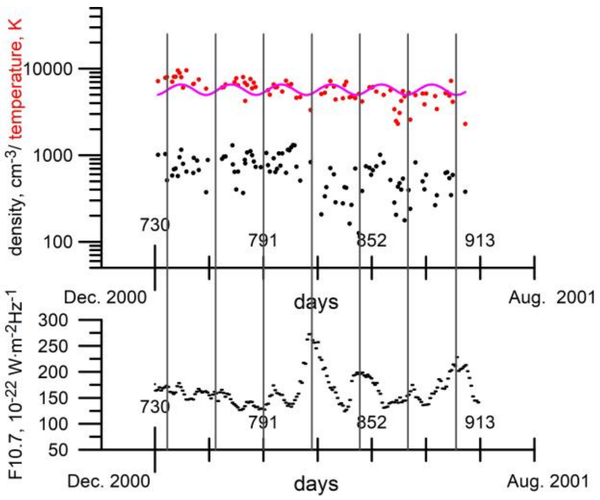

Figure 5. Proton temperature (top panel) and density (middle panel) variations measured by Magion-5 in the plane of the magnetic equator of the plasmasphere from January to June 2001. Along the X-axis are the days since 1999. The pink curve in the top panel indicates temperature data approximated by the sinusoidal dependence. Bottom panel depicts *F*10.7 variations [https://cdaweb.gsfc.nasa.gov/index.html]. Vertical lines are the beginnings of Carrington solar rotations, as observed from Earth [https://www.astroleague.org/iles/obsclubs/Carrington%20Rotation%20Start%20Dates.pdf]

Sinusoidal temperature variations from January to June 2001 with a period of ~28 days can be distinguished, but there is no noticeable correlation with *F*10.7. This is not surprising since the correlation of plasma temperature and density in the plasmasphere with *F*10.7 is poorly resolved (Figure 4, *b*, *c*).

Figure 6 illustrates the temperature (red dots) and density (blue) variations measured by Magion-5 and normalized to L=3 over the entire operation period of PL-48. The plot of proton temperature variations shows semi-annual variations with maxima in the vicinity of the equinox periods in spring (March 21) and autumn (September 23), but the annual period of temperature and density variations is also distinguished (highlighted by vertical dashed lines). The maximum in May–June 2000 prevails in the plot of density variations. This maximum, as in February–March 2001, is obviously a consequence of the midday density maximum (see Figure 2) since the measurements during this period were made in the daytime sector of the plasmasphere. Figure 2 shows that in the inner plasmasphere the plasma density dependence on local time is more significant than the seasonal dependence, at least in the longitude sector in which Magion-5 performed measurements (50° W – 60° E). The temperature dynamics seems to indicate the same thing. The local maximum proton temperature observed near the vernal equinox in early April 2000 (~460 days) was recorded at ~16–17 MLT. Then the temperature reaches a local maximum in the middle of August 2000 at ~6 MLT. At the same hours, temperature maxima are seen in Figure 2, *b*, although periods of these observations are close to the spring and autumn equinoxes.

Interball-1 made measurements not so frequently as Magion-5; therefore, the amount of data is insufficient to examine seasonal variations in plasmaspheric plasma parameters.

5. RELATIONSHIP OF ION DENSITY AND THERMAL PRESSURE IN THE PLASMASPHERE WITH SOLAR WIND DENSITY AND DYNAMIC PRESSURE

Despite Interball-1 crossing Earth's plasmasphere only once every four days and only at a sufficiently low perigee of the orbit, the long period of its operation makes it possible to analyze the dependence of cold plasmaspheric plasma characteristics on the parameters of the SW stream impinging upon Earth's magnetosphere.

Figure 7 plots the proton density (*a*, *b*) and thermal pressure (*c*), measured by Interball-1 in the plane of the magnetic equator of the plasmasphere, as function of the SW density N_{SW} (*a*) and dynamic pressure (*b*, *c*) ρV_{SW}^2 (p is the mass density, V_W *is* the SW velocity). Straight lines represent approximating dependences; while the black color (*a*, *b*) highlights the dependences obtained

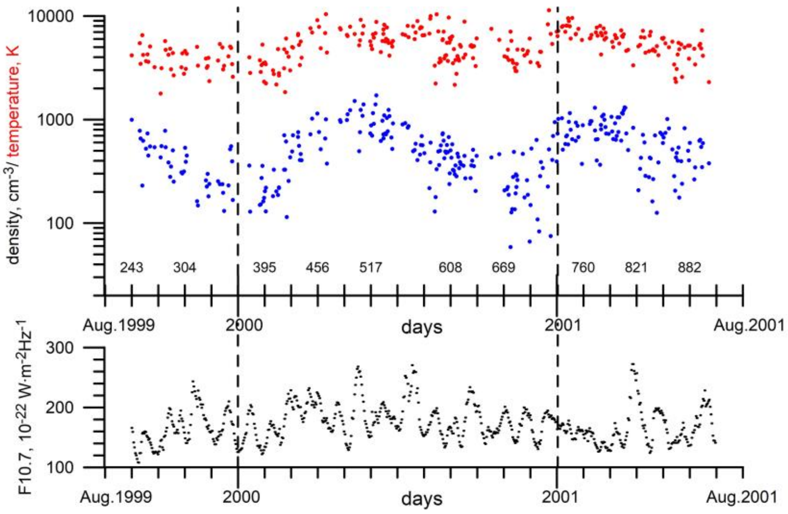

Figure 6. Proton temperature (red dots) and density (blue) variations, measured by Magion-5 in the plane of the magnetic equator of the plasmasphere, from September 1999 to June 2001. Along the X-axis are the days since 1999. The bottom panel illustrates *F*10.7 variations [https://cdaweb.gsfc.nasa.gov/index.html]. Vertical lines indicate a change of year

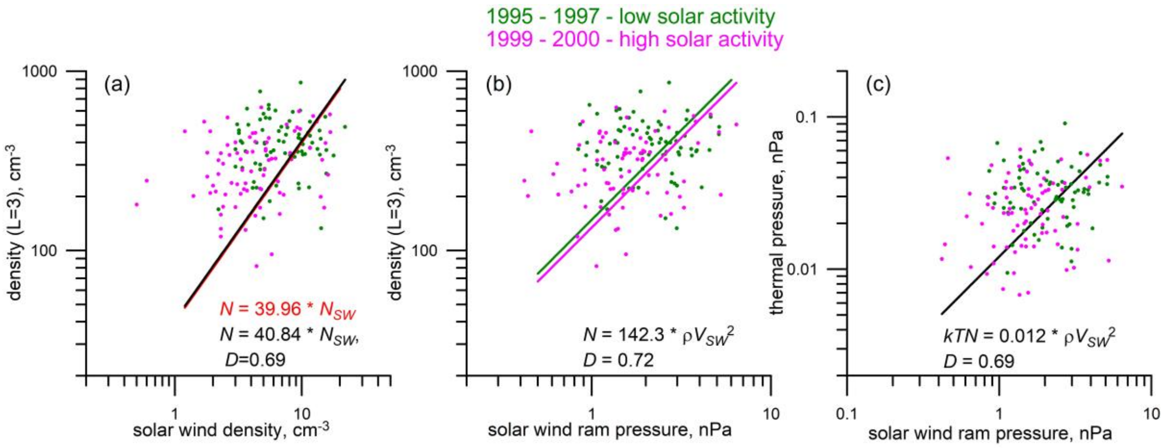

Figure 7. Proton density (*a*, *b*) and thermal pressure (*c*), measured by Interball-1 in the plane of the magnetic equator of the plasmasphere, as function of SW density N_{SW} (*a*) and dynamic (ram) pressure (*b*, *c*). The green color highlights measurements at solar minimum (1995–1997); purple, at solar maximum (1999–2000). Straight lines are approximating dependences

for all points (relations in black). Coefficients of determination *D* are also given for approximations of all measurements. In panel *b*, for example, the corresponding colors indicate approximations separately for measurements made during years of solar minimum and maximum. The dependences are seen to be similar. At the same time, it has been demonstrated once again that the thermal proton density in the plasmasphere during years of low solar activity is on average higher than during years of high solar activity.

The dependences shown in panels *a* and *b* are interrelated since the SW dynamic pressure depends largely on its density (Figure 8). The red line and the corresponding ratio in panel *a* are derived from the equations $N = 142.3\rho V_{SW}^2$ and $\rho V_{SW}^2 = 0.28 N_{SW}$. The calculated dependence practically coincides with the approximation obtained. Thus, it is impossible to say which dependence is the main one.

The dependence in panel *c* may be due to the dependence of the proton density in the plasmasphere on the SW dynamic pressure (*b*).

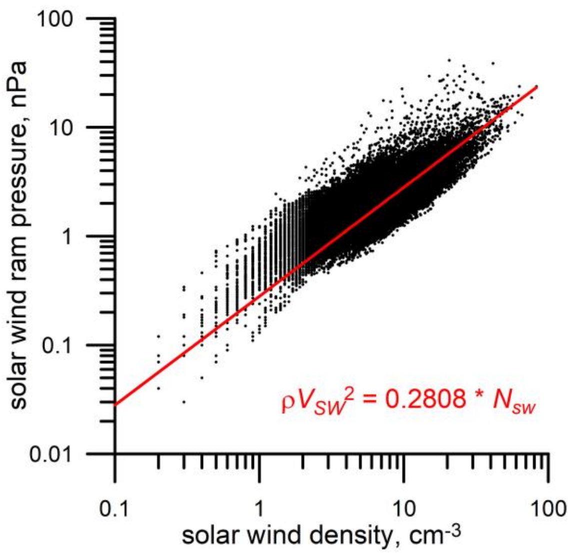

Figure 8. SW dynamic (ram) pressure as function of proton density on August 01, 1995–September 30, 2000

The Magion-5 data indicate the presence of the same relationships between the plasmaspheric plasma characteristics and the SW parameters, yet only for the dayside plasmasphere (Figure 9).

6. DISCUSSION

Using Interball data, we have tried to analyze in as much detail as possible various factors that have an effect on changes in the cold plasma density and temperature in the equatorial plane of Earth's inner plasmasphere. The main factor responsible for the distribution of cold plasmaspheric plasma density and temperature near Earth is the distance of magnetic plasma shells from Earth. To exclude the effect of the distance of the plasma measurement site from Earth, the data was scaled to the magnetic shell L=3. We analyzed the data obtained only inside the plasmasphere, but not near its boundary layer or in plasmaspheric plumes.

The second factor that can significantly affect the plasma distribution in the plasmasphere is the local time. The measurements carried out by Magion-5 during the years of high solar activity suggest that there is a strong dependence of the proton density on the local measurement time. The maximum density is observed at ~12 MLT; the density at night is on average 2–5 times lower.

Proton temperature variations in the inner plasmasphere as function of MLT are similar to diurnal variations in ionospheric temperature, which is confirmed by the analysis performed earlier in [Kotova et al., 2002a, 2008]. Magion-5 data has shown that the ion temperature in the plasmasphere at L<~2.5–2.8 is close to the electron temperature in the upper ionosphere at all MLT values, except for the midday-evening region (12–20 MLT), where the temperature in the plasmasphere is higher than in the ionosphere [Kotova et al., 2008]. The ratio of the ion temperature in the plasmasphere to the electron temperature in the upper ionosphere increases with L. During years of high solar activity, this temperature ratio increases faster than during years of low solar activity [Kotova, Bezrukikh, 2022].

The Interball-1 data, which relates to the period of high solar activity, confirm the diurnal proton density and temperature variations measured by Magion-5. However, it is possible that due to the noticeable difference between Earth's magnetic and geographic axes the ion density increase during daylight hours and diurnal temperature variations also depend on the geographic longitude of the site over which measurements are made. The available data is insufficient to verify this.

In addition to the two obvious factors that determine the plasmaspheric plasma density and temperature, solar and geomagnetic activity, as well as the SW stream impinging upon Earth and forming plasma and magnetic field distribution in the magnetosphere have a significant effect on cold plasma parameters.

According to Interball-1 data obtained during solar minimum and maximum of cycle 23, the proton density of the inner plasmasphere during the years of low solar activity was on average higher than during the years of high solar activity. Interball-1 measurements during minimum and maximum of the solar cycle are evenly distributed in local time. The spread of density values is quite large (see Figure 4). This result is inconsistent with that obtained earlier [Park et al., 1978] from ground-based Whistler measurements in 1957–1964. The results received from the data on the total electron content in the plasmasphere [Shim et al., 2017] depend primarily on determination of *PEC* that may or may not include the region of the upper ionosphere with a predominance of oxygen ions. The height of the transition from oxygen to hydrogen also depends on many factors.

A more likely reason for the difference between the Interball-1 data obtained during solar minimum and maximum and the wave measurements of electron density is the difference in the mass composition of plasmaspheric plasma during these periods. From Interball-1 measurements we determine only the proton density by calculating it through Maxwellian distribution approximation of the main peak in the ion energy spectrum [Kotova et al., 2014]. Meanwhile, various data has shown that with an increase in solar activity and F10.7 the relative content of helium and oxygen ions in the plasmasphere increases [Craven et al., 1997; Denton et al., 2025]. Due to the quasineutrality of plasma, the electron density is equal to the sum of densities of all positive ions, so with a significant increase in the number of heavier ions the proton density may decrease.

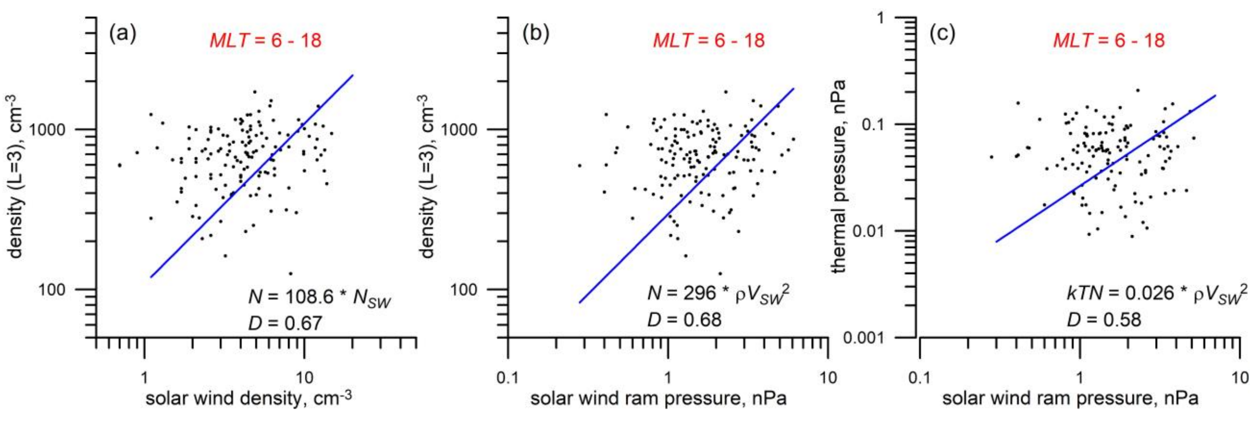

Figure 9. Proton density (a, b) and thermal pressure (c), measured by Magion-5 in the plane of the magnetic equator of the dayside plasmasphere, as function of solar wind density N_{SW} (a) and dynamic (ram) pressure ρV_{SW}^2 (b, c). Straight lines are approximating dependences

No trend was found in the proton temperature from comparison between Interball-1 measurements at solar minimum and maximum. More detailed Magion-5 data acquired during solar maximum does not indicate any dependence of ion density on solar activity, but suggests that both daytime and nighttime proton temperatures rise with increasing solar activity indices.

When analyzing the proton density and temperature variations measured by Magion-5 in the plane of the magnetic equator of the plasmasphere, it is impossible to determine seasonal variations during the years of maximum of the cycle (September 1999 – June 2001) since diurnal variations are clearly more significant, which apparently mask less significant seasonal variations in the parameters.

Sometimes we can detect 27-day temperature variations in the plasmasphere, but more data is needed for detailed analysis of such variations and their relationship with the solar EUV flux.

The data reviewed mainly relate to periods of low and moderate geomagnetic activity. Measurements performed during the main phase of magnetic storms on October 22, 1999 and January 13, 1996 with Interball-1, on October 15, 1999, June 26, 2000, August 29, 2000, March 20, 2001, and March 28, 2001 with Magion-5 (one flyby through the plasmasphere on August 13, 2000 during recovery from a strong storm (minimum *Dst*=–234 nT, August 12)), as well as measurements from this satellite during SSC on November 26, 2000, do not stand out from the rest of the plasmaspheric data. No dependence of the proton density or temperature of the inner plasmasphere on the geomagnetic activity indices K_p, *Dst*, *AE* was revealed. This, however, applies to the mean characteristics of the plasmasphere. In order to see changes in plasma characteristics in a single event, say, during one magnetic storm, it is necessary to measure plasma density and temperature in one region for a long time. Once in 6 hrs, such measurements were carried out by Interball-2 [Verigin et al., 2011]. It has been shown that during the main phase of magnetic storms the ion temperature of the plasmasphere generally decreases, whereas the plasma density increases or remains at the level characteristic of undisturbed conditions. We managed to explain this behavior of ion temperature, using a model of drift shell displacement from Earth caused by a decrease in the magnetic field in the inner plasmasphere during a magnetic storm.

Finally, let us turn to the dependence of the plasmaspheric characteristics on the SW parameters. Interball-1 data suggests that the plasmaspheric plasma density increases with increasing SW external (dynamic) pressure. The same dependence in the dayside plasmasphere is indicated by Magion-5 data. The SW pressure plays a major role in the interaction between the geomagnetic field and the SW stream. This interaction determines the shape of the magnetosphere, its compression from the daytime side, and the anti-sunward extended magnetotail. Nonetheless, inside the magnetosphere the cold magnetospheric plasma pressure is extremely low compared to the magnetic field pressure and cannot directly depend on the SW pressure. The formation of the plasmasphere and plasmapause is, however, significantly determined by the electric field of convection in the magnetosphere. The magnitude and distribution of this convection field in the magnetosphere depend presumably on SW pressure [Lukyanova, 2004]. It is likely in this indirect way that the SW pressure and density affect the density of cold protons. This issue requires serious theoretical analysis.

CONCLUSION

Using Interball-1 and Magion-5 data obtained in Earth's plasmasphere near the equatorial plane, we have analyzed possible causes of thermal (cold) proton density and temperature variations. The following results have been received.

The main factors responsible for cold plasma density and temperature variations in the equatorial plane of the plasmasphere include the distance of the magnetic shell from Earth and the local time. On average, proton temperature variations in the inner plasmasphere depending on MLT are similar to diurnal temperature variations in the ionosphere — maximum temperatures are observed after dawn and after noon. According to Magion-5 data, during the years of high solar activity the maximum proton density was observed at ~12 MLT.

In addition, the plasma density and temperature in the inner plasmasphere depend on the phase of the 11-year solar cycle. The proton density at solar minimum is on average higher than at solar maximum, which is likely to be due to changes in the mass composition of plasma in the plasmasphere and a decrease in the proportion of protons in the ion density during the maximum phase. Day and night proton temperatures increase with increasing solar UV flux, at least during the years of solar maximum.

The plasmaspheric plasma density and thermal pressure increase with increasing dynamic pressure and/or density of undisturbed SW, which is probably due to the restructuring of the convection electric field in the magnetosphere.

For a more complete study of the causes of variations in thermal plasmaspheric plasma characteristics, on the one hand, it is necessary to analyze data from ground-based and satellite wave measurements that allow us to determine the density of background plasma in order to assess the daily behavior of density in various longitude sectors throughout the solar cycle. Additional analysis of the behavior of plasmaspheric plasma temperature in the absence of new local plasma measurements should probably be carried out using data from previous experiments performed, for example, by the Dynamics Explorer-1, 2 (DE-1 and DE-2) satellites. On the other hand, to understand the causes of changes in the plasmasphere characteristics, it is necessary to theoretically analyze the physical relationships between processes in the magnetosphere and interplanetary medium.

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