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Experimental Results Indicative of Two Mechanisms of the Solar Wind Impact on Magnetosphere

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Abstract

The paper presents a short review of experimental data indicative of two independent mechanisms ensuring the solar wind influence on the magnetosphere, such as the reconnection of interplanetary (IMF) and terrestrial magnetic fields (Dungey,1961) and formation of the plasma pressure gradients in the magnetosphere as a generator of magnetospheric electric fields and currents (Tverskoy, 1972). According to spacecraft measurements, different Field-Aligned Current (FAC) systems act independently in the magnetosphere. The main is the R1 FAC system, operating within the magnetosphere irrespective of season and IMF orientation, the polar cap magnetic disturbances of DP0/DP2 type being permanently generated by this FAC system. The NBZ and BY FAC systems, observed at conditions of the northern (BZN) and azimuthal (BY) IMF influence, generate DP3 and DP4 magnetic disturbances, but only in the sunlit summer polar cap with the high-conductive ionosphere. The existence of the R1 FAC system, related to the plasma sheet within the magnetosphere, is logically treated in the framework of the Tverskoy concept, whereas the occurrence of the NBZ and BY FAC systems, related to the boundary layers of the magnetosphere, is explained in the framework of Dungey concept. To characterize the total solar wind energy input into the magnetosphere, the polar cap magnetic activity PC index, evaluated by the DP2 disturbances power, has been introduced. The PCN and PCS indices, derived online by data on DP2 disturbances in the Northern and Southern polar caps, are usually consistent, follow changes in the solar wind impact on the magnetosphere and well correlate with the development of magnetic storms and substorms. This makes it possible to regard the PC index as a proxy of the solar wind energy input into the magnetosphere. However, strong DP3 and DP4 disturbances in the summer polar cap, related to the mechanism of Dungey, occasionally distort the regular structure of DP2 disturbances, related to the mechanism of Tverskoy. It implies that the PC index derived in the winter polar cap (PCwinter) should be used to monitor the actual state of the magnetosphere.

Keywords: Solar wind - magnetosphere interaction; Mechanism of dungey; Mechanism of tverskoy; Magnetospheric field-aligned currents; Magnetic activity in northern and southern polar caps; Influence of solar wind parameters; PC index

Introduction

As soon as epoch of the space research started, it became evident that the geomagnetic disturbances are related to impact of the solar plasma fluxes (solar wind) on the Earth's magnetosphere [1-6]. It was noted that magnetic storms (DR) and polar magnetic substorms (DP) are usually observed under conditions of southward polarity of the Interplanetary Magnetic Field (IMF). Apart

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from magnetic substorms, the regular weak magnetic disturbances in polar caps were also revealed, which occurred to be connected with southward IMF as well these polar cap violations were named as DP2 disturbances to distinct them from magnetic substorms (DP1) observed in the auroral zone [7-11]. Three different hypotheses were suggested to explain these features of the solar wind influence on the magnetosphere state.

The first and the most known hypothesis is mechanism of magnetic reconnection put forward by Dungey (1961). According to this hypothesis, Interplanetary Magnetic Field (IMF) of southward polarity (BZS), transferred by solar wind, and the terrestrial magnetic field of opposite, northward polarity, are reconnected at the dayside boundary of magnetosphere. As a consequence, the interplanetary electric field EY = VSW x BZS (where VSW is the solar wind velocity) gains access into the boundary layer of magnetosphere. Since the interconnected field lines are transferred together with the solar wind, the ionospheric plasma, linked with these lines, moves in antisunward direction producing the appropriate ionospheric convection over the entire polar cap, which is equivalent to formation of the cross - polar cap potential. The merged field lines reconnect again in the tail neutral sheet, providing the return magnetic flow and the backward sunward convection in the auroral zone. As a result, two-vortices system of ionospheric convection is formed in the polar cap. In the framework of this concept the sunward convection, observed in a limited area of the near-pole ionosphere under the condition of northward IMF, is explained as a result of reconnection of the northward (BZN) IMF with the terrestrial magnetic field of southward polarity in the near-pole area of the magnetosphere.

According to the second hypothesis, known as the concept of “viscous-like interaction”, the solar wind momentum is transferred across the magnetopause and ensures the antisunward plasma convection on closed field lines along the boundary layer of the magnetosphere [12]. However, it was shown later that this mechanism can provide not more than 15% of the polar cap voltage and the viscous-like interaction is regarded at present as an ineffective mechanism [13-16].

The third hypothesis, formulated by Tverskoy (1972), was elaborated thereupon in studies [17,18]. According to the concept of Tverskoy, the permanent impact of solar wind on the magnetosphere violates magnetostatic equilibrium in the magnetosphere with the resulting formation of the plasma pressure gradients and corresponding large-scale electric fields, which generate within the magnetosphere the appropriate field-aligned currents responsible for the cross - polar caps dawn-dusk potential difference. It should be noted that the mechanism, suggested by Tverskoy, ensures the permanent, regardless of the IMF polarity, production of electric field and field-aligned currents within the magnetosphere in the course of uninterrupted solar wind – magnetosphere coupling. In fact, Tverskoy predicted existence of the magnetospheric field-aligned currents discovered later by Zmuda and Armstrong (1974) and Iijima and Potemra (1976 a, b) [19-21].

Concept of Dungey (1961) became popular at once, since it was the first hypothesis which gave explanation for the IMF influence on processes in the magnetosphere. Nevertheless, the numerous experimental facts, non-reconcilable with hypothesis of reconnection, were displayed, as example: plasma inside the magnetosheath (boundary layer separating solar wind and magnetosphere) demonstrates turbulent properties and there is rather common inconsistency between the polarity of magnetic fields outside and inside of magnetosheath, the plasma sheet turbulence is typical of geomagnetic tail, rate of reconnection between IMF and geomagnetic field is not controlled by the “interplanetary electric field” and so on [22-26].

Discussion between Dungey’s and Tverskoy’s concepts adherents extends over many years. Meanwhile, the experimental results are indicative of the independent action of both mechanisms. In this review-paper, we draw attention to experimental results concerning the field-aligned currents (FAC) systems in the magnetosphere and magnetic disturbances, produced by these systems in the polar caps. These results testify that the solar wind – magnetosphere coupling is realized through (1) the generation of the electric fields and field-aligned currents within the inner (closed) magnetosphere in correspondence with the mechanism of Tverskoy (1972) and (2) the generation of fields and currents in the external (polar) magnetosphere due to reconnection of the interplanetary and terrestrial fields in the boundary layer of the magnetosphere (Dungey, 1961).

Topography of magnetosphere

The terrestrial magnetic field is similar to the field of a giant geomagnetic dipole. When meeting the geomagnetic field, the fluxes of solar plasma, protons, and electrons, spreading in space, cannot directly penetrate the outer boundary of the geomagnetic field (magnetopause). That is why they are deflected around the geomagnetic field after having been slowed to subsonic velocities at the Earth's bow shock. The kinetic pressure of the shocked solar wind strongly compresses the dayside geomagnetic field. As this takes place, the magnetic field connected with polar caps is dragged out, under the action of the solar wind, toward the night side and forms the tail-like structure (magnetotail) stretched out to distances more than 100 RE. As a result, a cavity (magnetosphere) is formed in the solar wind, the size of the cavity being conditioned by a balance between the solar wind dynamic pressure and the terrestrial magnetic pressure in the transition region (magnetosheath) between the solar wind and geomagnetic field.

The solar wind impact on the magnetosphere is basically defined by such solar wind parameters as the solar plasma velocity (VSW) and the Sun's magnetic field, "frozen into" the solar plasma (usually named as interplanetary magnetic field – IMF). The complexity of these parameters determines the state of the magnetosphere. Under conditions of «quiet solar wind» (velocity of ~ 350 km/s) the geomagnetic field extends to a geocentric distance of (10-12) RE toward the Sun. Under conditions of "disturbed solar wind" (VSW ~ 800 km/sec) related to solar active areas, the magnetopause might come close to Earth up to 6 RE, with appropriate growth of influence of the external sources and generation of magnetic storms and substorms.

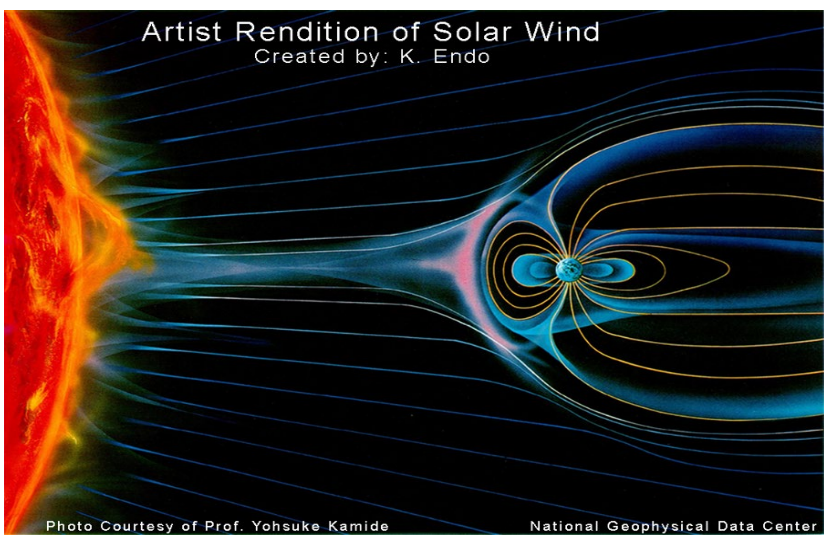

Figure 1. Schematic (non-scale) picture of the terrestrial magnetosphere in meridian section (Earth's radius is 6371 км, distance from Earth to Sun is ~ 150 000 000 кm). Geomagnetic field lines are shown by yellow threads, and solar plasma fluxes are marked by blue and pink lines and strips.

The magnetosphere, shown in Figure 1, can be subdivided into three parts.

1. The inner magnetosphere is region with closed field lines, where the physical processes are controlled mainly by the geomagnetic field.
2. The polar (external) magnetosphere is region, where field lines, connected with polar caps, are stretched out toward the night side and form a long geomagnetic tail (magnetosphere tail); the physical processes in this region are controlled, to a larger degree, by external sources, i.e. by solar wind.
3. The day-side polar cusp (or magnetosphere cleft) is a funnel-like region, which separates the inner (closed) and external (polar) magnetospheres. Likewise, the "night-side cusp" separates the adjacent "plasma sheet" region, positioned in closed magnetosphere, from the distant "neutral sheet", associated with open field lines in the northern and southern parts of magnetosphere tail. Since electrons and protons in the magneto sheath and cusp regions demonstrated the similar energetic spectra, the conclusion was made that the polar cusps serve as a channel providing the solar plasma delivery within the magnetosphere.

In framework of the Dungey's concept, the day-time cusp is a region, where the geomagnetic field lines of northward polarity, reconnected with southward IMF at the day-side magnetopause, are transported by solar wind into the polar magnetosphere. It implies that the day-time cusp and polar magnetosphere should be regarded, according to this concept, as regions with open field-lines connecting the terrestrial and interplanetary magnetic fields.

Form and location of the magnetopause and state of magnetosphere alter permanently under the uninterrupted impact of solar wind on the magnetosphere. The solar wind influence is realized through electric field and currents generated in the magnetosphere and ionosphere. The world magnetic storms (DR) are produced by powerful ring electric currents, flowing westward around the Earth at distance (3–8) RE. These ring currents produce the planetary decrease of horizontal H component of geomagnetic field at low and middle latitudes, named as Dst variation, with value in range (50 – 400) nT. Magnetic disturbances, typical of polar regions (DP), are related to the field-aligned currents (FAC), acting in the inner (closed) and external (polar) magnetosphere.

Magnetospheric field-aligned electric currents

Field-aligned currents systems

The field-aligned currents were revealed by evidences on transverse magnetic disturbances ΔB at altitude h=1100km [27]. The FAC patterns derived from observations on board the OGO spacecraft [19] were confirmed by data of the Triad spacecraft [20, 21]. The main Region 1 (R1) FAC system includes the currents disposed on poleward boundary of the auroral oval, the currents being flowed into ionosphere on the dawn side and being flowed out of ionosphere on the dusk side. The R1 field-aligned currents are observed at all times, irrespective of season and IMF polarity, the current intensity being increased under conditions of southward [19, 28, 20,21, 29,30]. The R2 FAC system, with currents directed oppositely to currents in the R1 FAC system, is developed at the equatorward edge of auroral oval in active periods. Figure 2 shows disposition of R1 and R2 FAC systems presented in Iijima and Potemra (1976a) [31].

Formation of R2 FAC system, related to enhanced precipitation of auroral particles in the auroral zone, leads to transformation of DP2 current system into DP12 FAC system and to development of substorm [32]. It is essential that the main FAC system features (spatial disposition and polarity of currents), typical of regular conditions, form the basis of the FAC patterns observed in substorm periods, the latitude extent of the R1 and R2 FAC patterns being increased by ~ 20÷30% [31]. During the substorm expansion phase the additional FAC system, named as "Birkeland current wedge", connected with the plasma sheet, is formed in the midnight sector of auroral zone (not shown in Figure 2) [33].

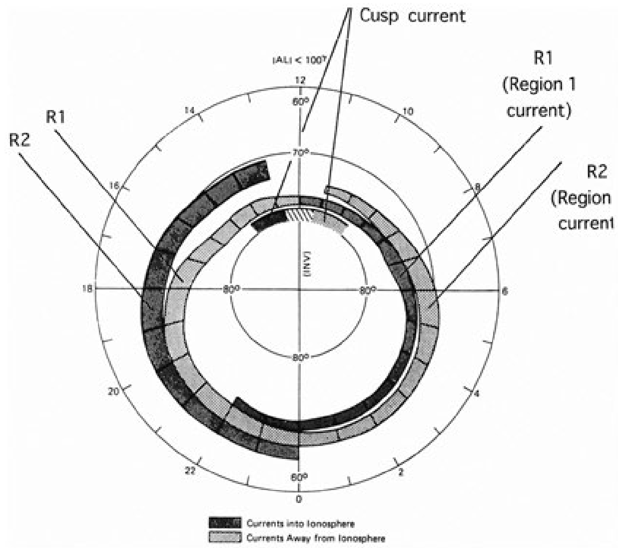

Figure 2. Systems of field-aligned currents derived from Triad data [20].

Under conditions of the azimuthal (BY) and northward (BZN) IMF influence on magnetosphere, the independent FAC systems appearin the day-time cusp region and in the limited near-pole area, correspondingly. The BY FAC system consists of two current sheets, located on the equatorward and poleward sides of the cusp ("cusp currents" in Figure 2). Direction of the field-aligned currents in these sheets, determined by sign of the IMF BY component, is opposite in the northern and southern hemispheres [34-37]. The NBZ FAC system (not shown in Figure 2) is disposed in near-pole region, at latitudes of $\Phi > 75°$ [36, 38-40]. Currents in the NBZ system are opposite in sign to currents in the R1 FAC system: they flow into the ionosphere in the post-noon sector and flow out of ionosphere in the pre-noon sector. The field aligned currents in BY and NBZ systems are closed in the polar cap ionosphere through the day-side cusp region (BY) and through the near-pole region (NBZ). As a consequence, power of the BY and NBZ FAC systems is occurred to be strongly dependent on the conductivity of the ionosphere in these regions.

Figure 3 presents schematically the disposition of the field-aligned currents in the summer northern polar cap for different IMF orientations (shown in centre of Figure) [41]. The lower pattern presents the location of the R1 and R2 FAC systems under conditions of southward IMF during magnetic disturbance, the upper pattern shows superposition of R1 and NBZ FAC systems under conditions of the northward IMF (period of magnetic quiescence), the left and right FAC patterns demonstrate effect of the negative and positive By IMF component influence on these current patterns: under conditions of positive BY IMF component (right side in Figure 3) the BY currents flow into the ionosphere at the equatorial boundary of cusp and flow out of ionosphere at the poleward cusp boundary, under conditions of negative BY IMF component (left side in Figure 2) polarity of currents is reversed. It should be born in mind that polarity of the BY field-aligned currents in the southern polar cap is the opposite.

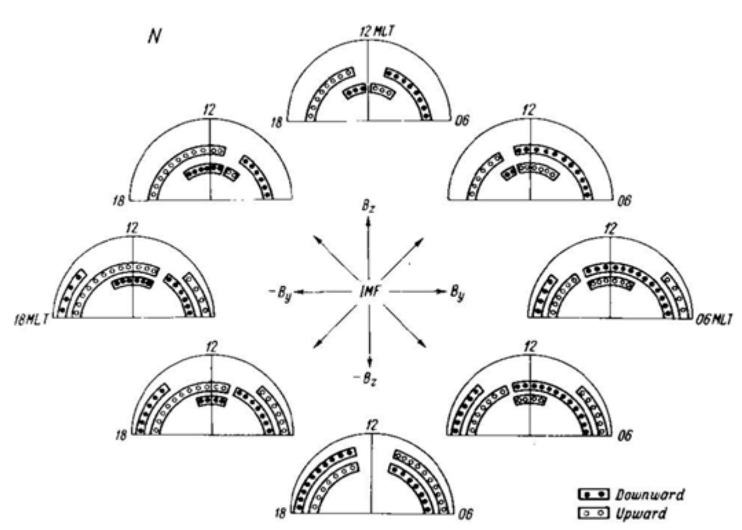

Figure 3. Scheme of the downward and upward field-aligned currents disposition in the northern summer polar cap for various IMF orientations [41].

Roots of FAC patterns in the magnetosphere

The R1/R2 FAC patterns were mapped on the equatorial section of magnetosphere by Potemra (1978) with use of the magnetosphere model (Fairfield and Mead, 1975), and by Antonova et al. (2006) with use of the magnetosphere models (Tsyganenko, 1996, 2002) [20, 42-46]. Results, presented in Figure 4, demonstrate that roots of R1 and R2 FAC systems are located within the magnetosphere, irrespective of distinctions between the magnetosphere models used in the analyses. The same result was obtained by Ohtani et al. (1995) while comparing the data of simultaneous FAC observations on board the Viking and DMSP-F7 satellites and by Chan and Russel (2000) basing on data on field-aligned currents measured by ISEE 1 and 2 satellites at altitudes (2-9) RE [47, 48]. Studies have demonstrated that R1/R2 FAC systems are connected with the plasma layer located in magnetosphere at geocentric distances ~7 RE– 10 RE [49-51]. The model simulations, as well as analyses of relationships between the field-aligned currents and plasma gradients are indicative of the magnetospheric plasma pressure gradients as a moving force for R1/R2 FAC systems [52-55]. Thus, results of all experimental and model analyses testify that the R1/R2 FAC systems are generated in the closed magnetosphere, in regions related to plasma pressure gradients, in agreement with concept of Tverskoy (1971).

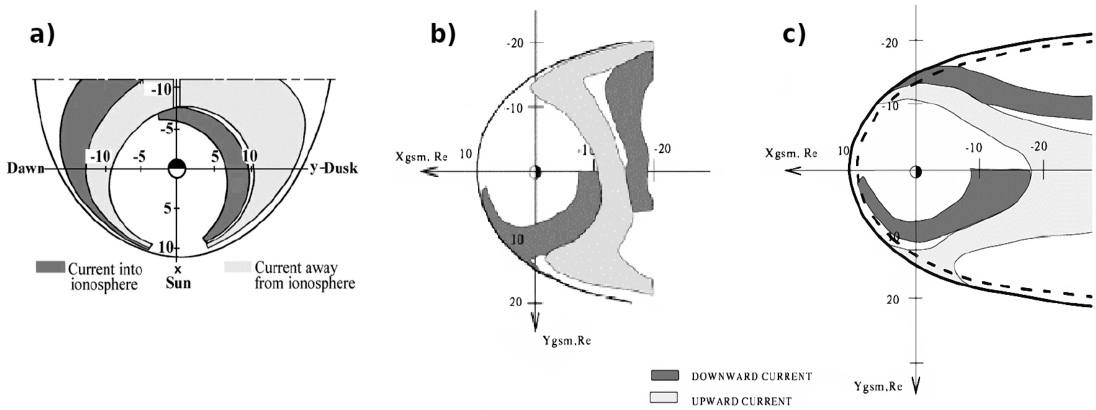

Figure 4. The R1 and R2 FAC patterns mapped into equatorial section of magnetosphere: (a) in (Potemra 1978) with use of the magnetic field model (Fairfield and Mead, 1975) and (b, c) in (Antonova et al., 2006) with use of magnetosphere models (Tsyganenko, 1996, 2002) [43-46].

On contrary, the BY and NBZ FAC systems, related to influence of azimuthal BY and northward BZN IMF components, are disposed in the polar regions related to boundary layers of magnetosphere, where (and when) the IMF polarity occurs to be contrary to polarity of terrestrial magnetic field [56, 57]. This circumstance suggests that the Dungey's mechanism is responsible for action of the BY and NBZ FAC systems. Notice that the original Dungey concept does not even refer to field-aligned currents on reason of the absence of any information about their existence at that time and processes specifying the link between the reconnection area and the field-aligned currents disposition are remained unclear up to now.

Seasonal variations of the field-aligned currents intensity

The field-aligned currents, acting in the magnetosphere, are closed through the high-latitude ionosphere. That is why the intensity of FAC currents is strongly dependent on conductivity of ionosphere in area, where the field-aligned currents are closed, the seasonal alterations being typical of all FAC systems. State of the field-aligned currents in winter, equinox and summer seasons has been perfectly displayed in study (Laundel et al., 2018), where the different model parameters were determined empirically with application of data of magnetic measurements on board satellites CHAMP for 2000-2010 [58-60] (see section 4.2).

Magnetic activity in the polar caps

Different types of polar cap magnetic activity: Three types of magnetic activity in polar caps, unconnected with substorms (DP1), have been revealed: DP2 disturbances related to southward BZS IMF DP3 disturbances related to northward BZN IMF and DP4 disturbances related to azimuthal BY IMF component [9-11, 61-67]. To characterize the structure of the polar magnetic disturbances, generated by ionospheric electric currents, the "equivalent current systems" are usually used, which are systems of hypothetical ionospheric currents providing the intensity and distribution of geomagnetic deviations observed in reality at the ground surface. Figure 5 shows the ionospheric current systems of magnetic disturbances, derived by data of magnetic observations on stations of northern polar cap in summer season: magnetic substroms DP1 (a), and polar cap magnetic disturbances DP2 (b), DP3 (c), and DP4 (d) [4, 63].

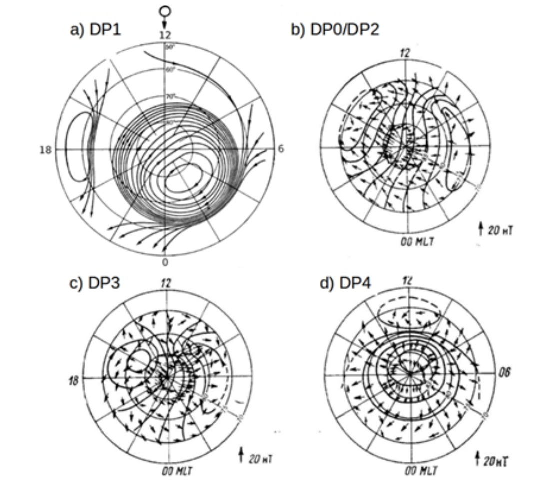

Figure 5. Current systems of the magnetic substorm DP1 (a) and polar cap magnetic disturbances DP2 (b), DP3(c), DP4 (d) observed in the northern polar cap in summer season. Distribution of vectors of magnetic disturbances on the ground surface is shown by short arrows [4, 63].

The DP2 current system (Figure 5b) consists of two vortices covering the entire polar cap, the currents in the near-pole region being sunward directed. The DP3 current system (Figure 5c) is composed of two current vortices of opposite polarity in the limited near-pole region. The DP4 system (Figure 5d) includes currents in the day-time cusp region (Φ~80°), the currents polarity, defined by sign of the BY IMF component, is opposite in the northern and southern polar caps. Multi-functional analysis of relationships between the IMF components and the polar cap magnetic disturbances reveals also existence of DP0 magnetic disturbances, similar to DP2, but independent on IMF [68]. Making allowance for the evident similarity of DP2 and DP0 disturbances, which are distinguished only by power of disturbances and, correspondingly, by the intensity of currents, the conclusion was made that DP0 and DP2 disturbances are generated by the same FAC system, the intensity of currents being regulated by southward IMF component. As the subsequent analysis showed, DP0 disturbances are controlled by the solar wind velocity [68, 69].

Polar cap magnetic activity and FAC systems

Availability of data on the field-aligned currents made it possible to fulfil the model computations of ionospheric electric field and currents generated by various FAC systems. Such analysis was performed with the use of FAC data and data on the conductivity of the polar cap ionosphere [20, 21, 70-72]. Results of numerical simulations, as well as results of analogous analysis of Kamide and Matsushita (1979), have demonstrated the full agreement of the model current systems with experimental current systems derived by the data of ground magnetic observations [63, 68, 70, 73]. As a consequence, the conclusion was made that the field-aligned currents are responsible for generation of magnetic activity in the polar cap [74, 41].

Figure 6 presents schematically the electric field systems generated by the FAC systems, shown in Figure 3, for conditions of geomagnetic quiescence (i.e. in absence of the R2 field-aligned currents) in the summer northern polar cap. The electric field systems are presented in form of convection patterns, where lines of convection are identified with electric potentials, the convection flows being opposite to the current directionality. The permanently operating R1 FAC system constantly generates the dawn-dusk electric field in polar cap and the appropriate DP0/DP2 current system with two almost symmetrical convection vortices (lower pattern in Figure 6). The identical DP2 disturbances are observed in the northern and southern polar caps, the power of disturbances being higher in summer sun-lit polar cap with high-conductivity ionosphere. The R1 FAC power and, correspondingly, the intensity of ionospheric DP2 currents increases under conditions of southward IMF.

The NBZ FAC system generates the DP3 current system with currents opposite in direction to DP2 currents, but only in summer polar cap, where high conductivity of sunlit ionosphere ensures fine conditions for the NBZ field-aligned currents closure. The DP3 system is confined to near-pole area; simultaneous operation of R1 and NBZ FAC systems results in formation of the four-vortex DP2+DP3 convection system in the summer polar cap (upper pattern in Figure 6). Influence of the azimuthal BY>0 IMF strengthens the convective flow in the dawn sector of auroral oval (right patterns). Under conditions of BY<0 IMF the convective flow increases in the dusk sector of the oval (left patterns). The regularity is reversed in the southern polar region. As a result of the BY IMF influence, the electric field orientation in the near-pole ionosphere (and direction of the magnetic disturbance vector δF) can change up to 90°.

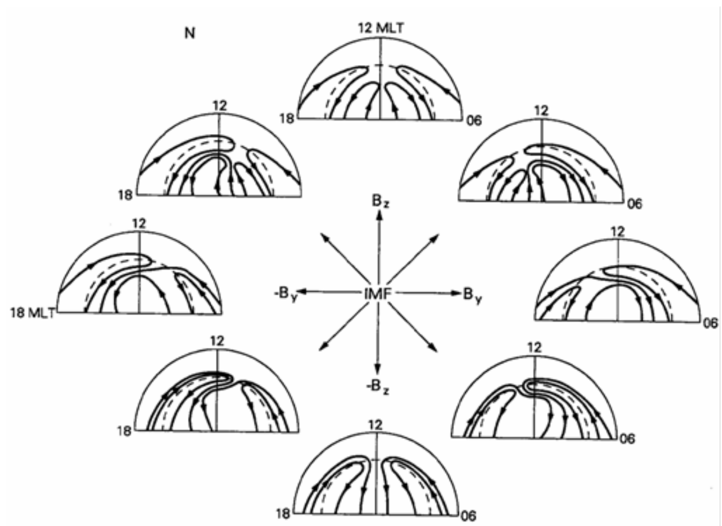

Figure 6. Convection patterns in the northern summer polar cap in the quiet period under conditions of different IMF orientations [41].

These results were confirmed and refined by data of subsequent magnetic observations on board Dynamics Explorer 2 spacecraft, Iridium constellation of spacecrafts and satellites CHAMP and Swarm [75-78]. As example, Figure 7 demonstrates distribution of the field-aligned currents (red – upward, blue - downward) and corresponding divergence-free ionospheric (Hall) currents (black contours) in the summer (a), equinox (b) and winter (c) high-latitude ionosphere (Φ>60º), obtained by Laundal et al. (2018) for different IMF orientations (shown in centre of Figure) under conditions of the lowest solar activity: solar wind speed VSW=350 km/s, interplanetary magnetic field |B|=4 nT, the solar index F10.7=80 [78]. Presented patterns are based on data of the geomagnetic field vector observations (N = 50 518 182) with application of AMPS (Average Magnetic field and Polar current System) model (Laundal & Toresen, 2018).

One can see the permanent availability of the R1 FAC system with field-aligned currents flowing into ionosphere in the morning pole-ward boundary of auroral oval and flowing out of ionosphere in the evening boundary. Intensity of the R1 currents is controlled by season and by IMF polarity: under conditions of BY=0 and southward IMF the maximal R1 FAC intensity varies from (0.40-0.45) μA/m2 in summer to (0.28-0.30) μA/m2 in winter, under conditions of BY=0 and northward IMF the R1 FAC intensity varies from (0.36-0.39) μA/m2 in summer to (0.05-0.07) μA/m2 in winter.

Unlike to R1 FAC system, the BY and NBZ FAC systems are formed only under conditions of the azimuthal or northward IMF influence, correspondingly. The NBZ system, with currents sense opposite to the R1 FAC polarity is disposed in the day-side near-pole region against the background of the large scale R1 FAC system. As a result, the four-vortex DP2+DP3 ionospheric current system is produced in summer season (Figure 7a). Since NBZ field-aligned currents are closed in the near-pole region, their intensity is strongly dependent on the ionospheric conductivity and NBZ FAC system is not practically registered in the winter polar cap.

Strong dependency of R1 currents on the IMF BY and BZ components is evident. The BY FAC system influence is expressed, as increase of field-aligned currents flowing into ionosphere in the morning auroral oval for conditions BY>0, and as increase of currents flowing out of ionosphere in the evening auroral oval for conditions BY<0. As a result, intensity of the R1 field-aligned downward currents in the dawn auroral oval reaches values (0.51, 0.44, 0.37) μA/m2 in summer season, (0.29, 0.29, 0.28) μA/m2 in equinox season, and 0.14, 0.19, 0.25 in winter season for conditions BZ>0, BZ=0, BZ<0. The appropriate values of intensity of the R1 field-aligned upward currents in the dusk auroral oval for conditions BZ>0, BZ=0, BZ<0 is the following: (0.55, 0.51, 0.44) μA/m2 in summer, (0.26, 0.27, 0.27) μA/m2 in equinox, 0.08, 0.13, 0.22 in winter. In the southern hemisphere, with contrary polarity of the BY field-aligned currents, the effect of the BY IMF influence is opposite. It should be borne in mind that all these values, referred to conditions of magnetic quiescence, are strongly increased in active periods. The evident conclusion follows from these experimental data that state (disposition and intensity) of the R1 FAC system, acting within the magnetosphere, and appropriate ionospheric current systems, generated in the polar caps, is determined by influence of both BY and BZ IMF components.

Thus, results verify conclusions made in that structure of the polar cap magnetic disturbances and their intensity are determined by the corresponding FAC systems acting in the magnetosphere [70, 71, 78]. Therefore, the DP2 disturbances, permanently generated by R1 field-aligned currents in polar caps could be used as indicator of the solar wind influence on the magnetosphere [63, 68].

The polar cap magnetic activity PC index

Analysis of relationships between DP2 disturbances and solar wind parameters showed that DP2 disturbances well correlate with various “coupling functions” [79].

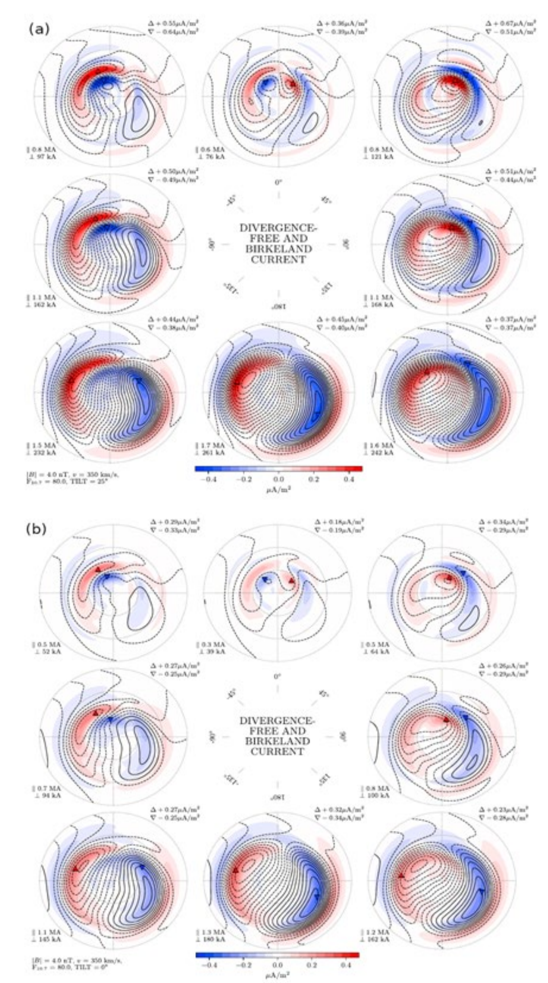

Figure 7. Field-aligned current (red and blue color) and the ionospheric Hall currents (black contours), in the Northern Hemisphere in summer (a) and winter (b) seasons [78]. The peak upward and downward current densities are listed in the top right corners. Total upward current, labeled by ∥, is given in the lower left corners in units of megaampere. The ionospheric currents are labeled by ⊥ in units of kiloampere. Each map shows the apex North Pole at the center, with latitude circles indicated at 80º, 70º, and 60º, proposed to estimate the efficiency of the solar wind – wind-magnetosphere coupling, but the best correlation takes place with "merging electric field" EKL, suggested by Kan and Lee (1979) [80]:

$$EKL = VSW*(BY2+BZ2)1/2sin2\theta/2 \quad (1)$$

where θ is the clock angle between geomagnetic dipole and IMF tangentional component BT=(BY2+BZ2)1/2. Notice that expression for EKL field includes the squared values of the azimuthal BY and vertical BZ IMF components, the IMF orientation being taken into account through angle θ. It implies the probability of high values of EKL field even at northward BZS IMF component under condition of favorable orientation and value of the azimuthal BY IMF component, as it was demonstrated by results [78].

It should be kept in mind that the "merging electric field" EKL is not a real field, carried by the solar wind; it is only one of many "coupling functions", inaccessible for direct measurements. Just "coupling function" EKL, making allowance for all geoeffective solar wind parameters (BY and BZ IMF components, solar wind velocity vSW, angle θ), occurred to be the optimal combination of the solar wind parameters ensuring the highest power of the polar cap DP2 disturbances, generated by R1 FAC system. As a consequence the EKL function was chosen, under the name “solar wind electric field”, as a parameter determining the power of DP2 magnetic disturbances and the appropriate polar cap magnetic activity index PC was put forward into practice [79, 81].

The statistically justified relationships between the EKL field and DP2 magnetic disturbances in the northern and southern polar caps have been examined on the basis of data on the solar wind parameters (http://omniweb.gsfc.nasa.gov) and data on magnetic activity at the polar cap stations Thule (Greenland) and Vostok (Antarctica) for 1995-2005 with use of “unified PC index derivation method” [82]. In so doing the daily and seasonal variations of ionospheric conductivity at stations Thule and Vostok have been taken into account. The calibration coefficients determining link between the values of EKL field and the DP2 disturbances for any moment of each day of year have been used for calculations of the PCN and PCS indices. This circumstance has defined consistency of the corresponding PCN and PCS indices and their conformity with appropriate EKL field value in any current moment of time, irrespective of quite different conductivity of ionosphere in summer and winter polar caps.

Subsequently the close relation between the dynamics of the PC index and development of magnetic storms and substorms was shown [83-87]. In particular, it was disclosed that “extraordinary magnetic disturbances”, observed under conditions of northward IMF are usual phenomena occurring when the index exceeds the critical value PC ~ (1.5 ± 0.5) mV/m, which is necessary for substorm development [83, 84, 88-90]. It was revealed also that the early mean values of EKL field and PC, AE, Dst indices correlate with the total IMF field |B| ($R = 0.96 \div 0.86$) much better than with IMF BZ component ($R= 0.81 \div 0.69$) [91]. The mean correlation between the EKL field and PC index over 24 years (1998-2021) turned out to be R=0.85-0.90, like to the correlation revealed for 23rd cycle [92, 93]. All these results demonstrate that PC index can be regarded as “a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling” as it was certified by International Association of Geomagnetism and Aeronomy [94, 95].

Since the PC index is evaluated by value of DP2 magnetic disturbances related to EKL field, it implies that (1) EKL field is a basic “coupling function” determining the total solar wind impact on magnetosphere, (2) DP2 disturbances are generated in polar caps by the R1 FAC system permanently acting within the magnetosphere, and (3) mechanism of permanent formation of the electric fields and R1 field-aligned currents within the magnetosphere is apparently related to arrangement of the appropriate plasma pressure gradients in magnetosphere under the persistent solar wind impact on magnetosphere, as it was suggested by Tverskoy (1972).

Irregular discrepancies between values of PCN and PCS indices and their reason

Although the “unified method” made allowance for difference of ionospheric conductivity in the summer and winter seasons while deriving PC index, the irregular discrepancy between the PCN and PCS values turned out to be a common phenomenon, [82, 83, 96]. Figure 8 shows, as example, the courses of the daily mean values of PCN, PCS indices and their difference ΔPC=PCN-PCS in years of the solar activity maximum (2015) and minimum (2019). Though the PCN (blue) and PCS (red) indices are changed in good agreement with the EKL field (black), difference between the appropriate values of PCN and PCS can be significant, especially in epochs of solar maximum. In so doing the values PCS exceed PCN during summer season in southern hemisphere (November/December/January/February), and values PCN exceed PCS during summer in northern hemisphere

(May/June/July/August). These results imply that value ΔPC is determined by season, the discrepancy being the highest (>1 mV/m) during the solar maximum.

Analysis of physical reasons of this seasonally dependent discrepancy was carried out in (Troshichev et al, 2023) with use of daily mean values of difference ΔPC= PCN-PCS for 22 years (1997-2019) [96]. Results of analysis pointed to effect of the IMF BY component as a reason of the discrepancy: values ΔPC were positive (PCN>PCS) in case BY>0 and negative (PCS<PCN) in case BY<0. The positive and negative ΔPC quantities are linearly increased with growth of the corresponding (positive or negative) BY IMF component, with correlation R> 0.95 between the ΔPC and BY values for category of positive PCN and PCS indices (75% of events). As for the EKL field influence, values ΔPC demonstrate increase with the EKL growth, but irrespective of season and the PC index category.

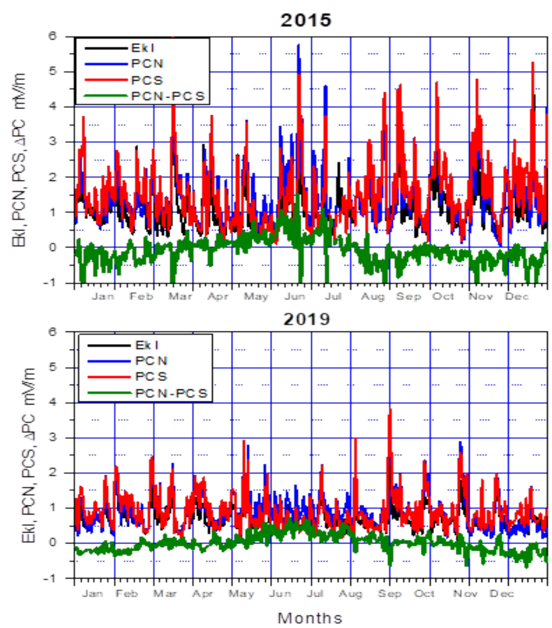

Figure 8. Courses of daily values of the PCN (blue) and PCS (red) indices and difference (PCN-PCS) (olive) in epochs of solar maximum (2015) and solar minimum (2019) [96].

It is evident that seasonal effect of the BY IMF influence on PC index value is related to variation in intensity of the BY-dependent FAC systems, defined by seasonal changes of ionospheric conductivity in polar caps, as it was demonstrated in Figure 7. However, in case of R1 FAC system this effect has been taken into account by the application of the “unified method” while deriving the PC index [82]. It means that seasonal dependency of the PC index values is caused by the independent BY FAC system, which intensity is maximal in the sunlit polar cap and minimal in the dark polar cap; as this takes place, the effect, determined by sign of the BY IMF component, is opposite in the northern and southern hemispheres. As a result, the DP4 disturbances, related to BY field-aligned currents, strongly distort the regular DP2 convection patterns in the summer polar cap, the sign of discrepancy ΔPC=PCN-PCS being defined by sign of the BY IMF component.

Therefore, the discrepancy between values of the appropriate PCN and PCN indices derived in the summer and winter polar caps is caused by distorted effect of the independent BY (and NBZ) FAC systems, which operates in polar magnetosphere due to "interconnection mechanism" (Dungey, 1961) acting in the boundary layers of magnetosphere. The likelihood of possible distortion of the PC index value in the summer polar cap presumes that the PC index in winter polar cap (PCwinter) should be taken as a preferential characteristic to estimate the solar wind geoefficiency. Indeed, analysis of relationships between the PCN/PCS indices and AL index for each month in period 1998-2017 showed that the substorm progression is better ensured by PCN index during northern winter (November–February), and by PCS index during southern winter (April–July), irrespective of choice of station (Thule or Vostok). It means that the PC winter index should be used to monitor the magnetosphere state [97].

Discussion

Experimental data, examined above, demonstrate that R1 FAC system acts continuously, irrespective of the IMF polarity. As this takes place, the NBZ and BY FAC systems act only under appropriate influence of the northward BZN or azimuthal BY IMF components, correspondently. It is essential that R1 FAC system is positioned within the inner (closed) magnetosphere, whereas the NBZ and BY FAC systems are observed in polar (open, according to Dungey concept) magnetosphere. The latter peculiarity determines quite different response of these FAC systems to seasonal variation of ionospheric conductivity. The R1 FAC intensity indecisively decreases while passing from summer to winter, since the morning and evening branches of the oppositely directed R1 field-aligned currents close in winter periods through sufficiently well conductive auroral zone [98]. In contrast, the NBZ intensity falls critically in winter season, since closure of the NBZ currents occurs through low-conductive ionosphere in the dark polar cap.

Specific situation is observed in summer hemisphere, under conditions of northward IMF, where two FAC systems, with oppositely directed currents, operate simultaneously: the R1 system acts in the auroral oval, whereas NBZ system acts in the near-pole area. It is evident that in this case "reconnection" can occur only in the polar magnetosphere, where IMF is opposite in direction to terrestrial field, but not in the dayside magnetopause, where IMF and terrestrial fields are northward directed. Moreover, the R1 FAC system continues to operate in the winter season, whereas NBZ system disappears in fact. Just these experimental facts give conclusive evidence of two independent mechanisms of generation of the field-aligned currents.

The experimental data, demonstrating different location of the R1 and NBZ/BY FAC systems in magnetosphere and divergent response of these systems to the IMF polarity and season, indicate the probable mechanisms of the solar wind influence on the magnetosphere. The constantly available R1 FAC, related to plasma sheet within magnetosphere, can be regarded as result of permanent formation of the plasma gradients and the appropriate electric fields within magnetosphere in course of permanent solar wind impact on the magnetosphere, in line with concept of Tverskoy. The NBZ/BY FAC systems, generated in polar magnetosphere only under conditions of the northward or azimuthal IMF influence, can be regarded as a consequence of reconnection of the terrestrial and interplanetary magnetic fields in those boundary layers of magnetosphere, where these fields occurred to be contrary oriented, in line with concept of Dungey.

As experimental data demonstrate, the R1 FAC intensity increases under conditions of southward BZS IMF component. This peculiarity is explained, first of all, by close relation of the R1 FAC system to the "coupling function" EKL =VSW*(BY2+BZ2)1/2sin2θ/2. The reconnection mechanism may be operable as well, but in this case, the problem arises with the location of the reconnected field lines and corresponding field-aligned currents. According to Dungey's concept, as soon as the northward geomagnetic field reconnects with the southward IMF on the day-side magnetopause, the reconnected field lines are transferred by the solar wind into the polar (open) magnetosphere, connected with IMF. It implies that the corresponding FAC system, related to the reconnection mechanism, should be disposed of, like to BY and BZN FAC system, in the open magnetosphere, however all experimental data indicate that R1 FAC system is arranged in the auroral zone, i.e. in the closed magnetosphere.

There is the possibility that a specific "SBZ" FAC system is formed on the outside of the auroral oval boundary, but availability of such a FAC system is not revealed in the spacecraft experiments due to the impossibility of separating the "SBZ" FAC system effect against the background of the adjacent R1 FAC system issue. In such a case the summary effect of R1 and assumed "SBZ" FAC systems is regarded as an increase of the R1 FAC intensity under conditions of southward IMF. To prove the action of the reconnection mechanism the independent "SBZ" FAC system should be revealed on the outside of the auroral boundary of the closed magnetosphere.

Conclusion

- Mechanisms of the "plasma pressure gradients formation" (Tverskoy, 1972) and" magnetic interconnection" (Dungey, 1961) operate simultaneously and independently. Mechanism of Tverskoy ensures the permanent generation of the electric fields and currents within the magnetosphere in course of permanent solar wind-magnetosphere coupling, whereas mechanism of Dungey, related to the IMF polarity, ensures interaction between solar wind and magnetosphere only in those parts of boundary layer of magnetosphere, where the IMF is opposite in direction to the terrestrial magnetic field.
- Mechanism of Tverskoy is responsible for the R1 FAC systems, operating irrespective of the IMF polarity and season, the R1current intensity being depended on solar wind velocity and BZ and BY IMF component; the R2 FAC system is added during magnetic substorms. Mechanism of Dungey is responsible for the BY/NBZ FAC systems, which are observed only under conditions of the IMF BY and BZN influence and mainly in summer (equinox) polar cap, when conductivity of ionospheric reaches essential value.
- The PC index, introduced as indicator of the DP2 disturbances, generated by R1 FAC system, makes it possible to estimate the total solar wind influence on the magnetosphere, arranged by mechanism of Tverskoy. Efficiency of this influence is characterized by function "EKL field", which includes all geoeffective solar wind parameters.
- The BY/NBZ FAC systems, acting under conditions of the azimuthal/northward IMF influence, distort regular structure of DP2 disturbances in the summer polar cap, resulting in imprecise estimation of the PCsummer index. The most simple and reliable way to exclude from examination the distorting effect of "magnetic reconnection" is application of the PC index in winter polar cap (PCwinter index).

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