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On Contribution of Poloidal Branch of Solar Activity to Heliosphere and GCR Modulation

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Abstract. The point of view is substantiated that during periods of low sunspot activity many heliospheric characteristics (the solar wind velocity, the form of the heliospheric current sheet, the strength of the heliospheric magnetic field) can be considered as the manifestations in the heliosphere of the poloidal branch of solar activity. As these characteristics strongly influence the process of the GCR transport through the heliosphere the contribution of the poloidal branch of solar activity to the GCR solar modulation should also be substantial. This conclusion is at odds with the wide-spread belief that the modulated GCR intensity is mainly determined by the sunspot cycle.

1. Introduction

When describing the cycle of solar activity on photosphere and in the underlying layers of the Sun two topologically different systems (or branches) of magnetic fields are isolated: toroidal, B_{φ}^t , and poloidal, $B_{r,\vartheta}^p$ [1]. These two systems are connected by motion of solar plasma, namely its differential rotation, convection etc. In the characteristics of these two systems of solar magnetic fields (SMF) observed on photosphere the toroidal branch corresponds to the active regions with the sunspots etc., while the poloidal branch corresponds to the coronal holes, high-latitude SMF, zonal unipolar magnetic regions etc. [1]. The properties of these two SMF branches are rather different both in their characteristics (scale and strength) and time behavior. Note that usually, speaking of the solar activity cycle, its maxima and minima, one has in mind the characteristics of toroidal branch of solar activity, because of its much more powerful manifestations (flares, coronal mass ejections) on the Sun and near the Earth.

However, the modulation of the GCR intensity takes place in the outer layer of solar atmosphere – heliosphere. For more than 60 years of the heliospheric and cosmic ray studies a huge amount of experimental data and theoretical ideas has been accumulated, but the picture of the 11-year cycle in sunspot activity as the root cause of long-term GCR variations is repeated from paper to paper (see review [2]). Small observed 22-year effects in GCR are usually associated with variation of the polarity of heliospheric magnetic field (HMF). The causes of such situation are discussed in [3].

In [4] the point of view was suggested that during periods of low sunspot activity many principal heliospheric phenomena connected with the global heliospheric current sheet (GHCS) – the inhomogeneous solar wind (SW) velocity with respect to GHCS, the division of the heliosphere into two unipolar hemispheres with opposite polarity of the magnetic field – could be considered as the manifestations in the heliosphere of the poloidal branch of solar activity.



In this paper we first briefly consider the cause of different manifestation of two activity branches in the heliosphere and underlying spatial layers and then add the HMF strength to the list of heliospheric characteristics with the substantial contribution of the poloidal solar magnetic fields. As these characteristics strongly influence the process of the GCR transport through the heliosphere the contribution of the poloidal branch of solar activity to the GCR solar modulation should also be significant. More extended version of this paper will be published elsewhere.

2. Heliosphere as an outer layer of the Sun

It is wellknown that there is a counter-phase development of the toroidal and poloidal branches of solar activity [1]. Both of these SMF systems demonstrate the inversions of their magnetic fields. The azimuthal SMF of the toroidal branch changes its sign in the sunspot minimum, when the polarities of the preceeding and following spots of the bipole group reverse. The radial SMF of the poloidal branch in each polar regions changes sign in the sunspot maximum. However, in spite of the much more powerful toroidal SMF, the HMF polarity (which is important for GCRs) reflects that of the poloidal, but not toroidal branch of solar activity [5]. To understand this phenomenon we should consider the radial dependence of different types of the energy density.

As can be seen from the data in Fig. 1, there are roughly equal densities of thermal and magnetic energy at photosphere ($r = r_\odot$), but then, up to distances of the order of $r_{HS} \approx 10r_\odot$, the major dynamic factor is the magnetic field. At the same time in this layer, which we call the basement of the heliosphere, the SW velocity increases. Starting with the inner heliospheric boundary $r = r_{HS}$ and up to the heliopause $r = r_{HP}$ the heliosphere extends, where the major dynamic factor is supersonic and superalfvenic (except in the heliosheath) solar wind. Beyond the heliopause is a very local interstellar medium (VLISM). Such spherically symmetric geometry of the heliosphere is broken due to movement of the Sun relative to VLISM, as well as the latitude dependence of the SW characteristics. It leads to the complex structure of the heliosphere.

Thus, to clarify the issue of the relationship between the manifestations of two branches of activity on the Sun and in the heliosphere, the processes in the basement of the heliosphere are of crucial importance. In the model of potential SMF with a surface source worked out in Wilcox Solar Observatory (WSO) [7] and widely used to study GCR variations, the absence of currents is assumed in the basement the heliosphere, $r_\odot \leq r \leq r_{SS}$, where r_{SS} is the radius of so-called source surface. Then everywhere in the basement all three components of SMF, $B_{r,\vartheta,\varphi}$, can be calculated in potential approximation using the sets of the coefficients published in [7].

Note that partly due to the complete absence of currents and too small r_{SS} assumed in the model the absolute value and coordinate dependence of $B_r(\vartheta, \varphi)$ on the source surface, based on the WSO model, do not correspond to the observations [8] and are not commonly used. However, according to observations at spacecraft Ulysses, Pioneers, Voyagers the shape of the calculated neutral line $B_r(\vartheta, \varphi) = 0$ on this surface in the first approximation corresponds to the form of the heliospheric current sheet (HCS) [5, 9], and it is widely used in GCR studies. We make extensive use of two types of results of the WSO model: neutral isolines on the source surface and magnetic field flux through the photosphere and source surface. When calculating SMF fluxes we are also interested in the contribution of dipole SMF. Neutral isoline on the source surface is regarded as the base of the HCS. In [10], using the WSO model, we suggested the classification of the HMF polarity distributions and the meaning of the HMF inversion.

If using the WSO model we compare the distributions of SMF radial component on photosphere and source surface during periods of intermediate and low sunspot activity, we can see a complex distribution with numerous small islands of SMF of opposite polarities, neutral lines etc. on photosphere, while on the source surface there are only two hemispheres of opposite SMF polarity divided by single global neutral line. Hence the main function of the heliospheric basement is to filtrate the magnetic fields by their scales. So in the transition from photosphere

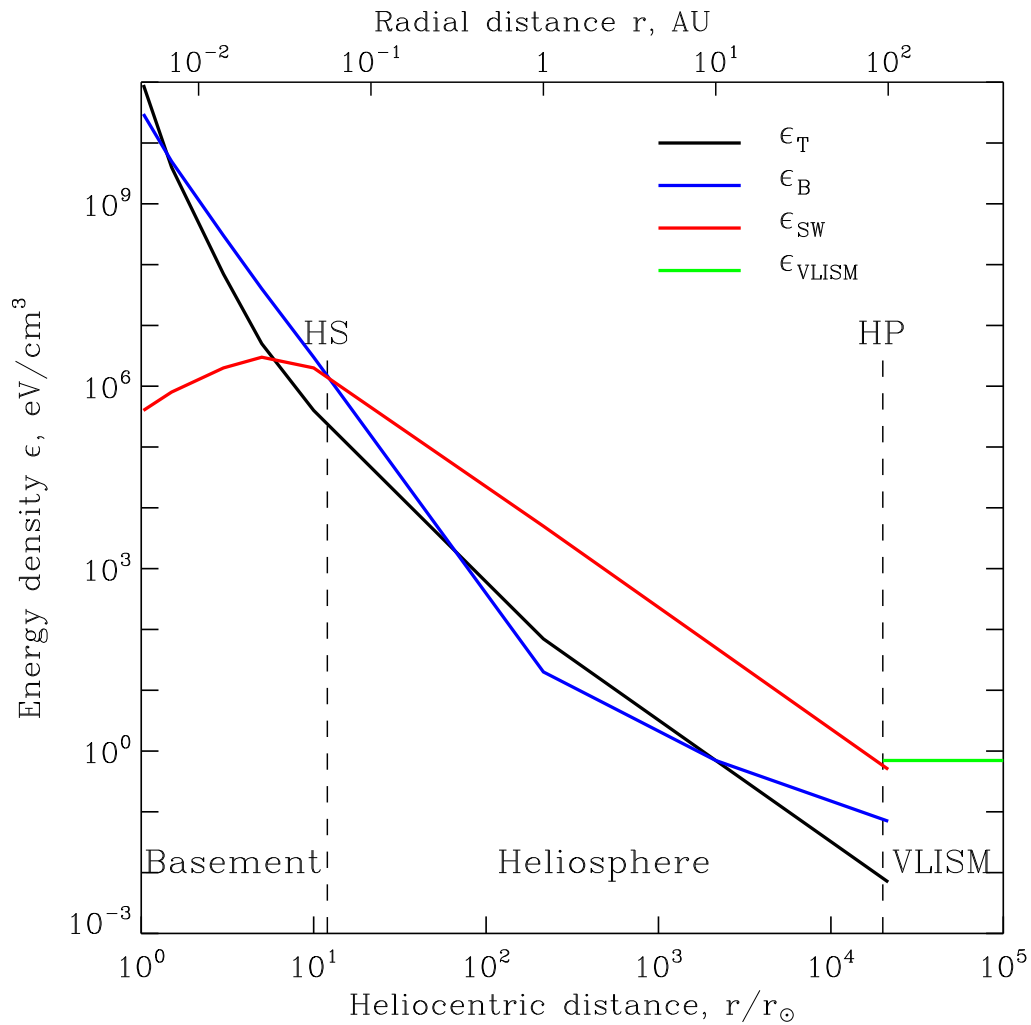


Figure 1. The heliocentric radial dependence of density of the different types of energy (thermal, magnetic, kinetic, interstellar), mainly based on [6]. The vertical dashed lines show the approximate positions of the heliospheric boundaries.

to heliosphere the poloidal SMFs due to their larger scale get the advantage over the toroidal ones. The second main function of the basement is that in this layer the form of the SMF tubes open to the heliosphere greatly affects the SW accelerating along these tubes [11].

3. Branches of solar activity and heliospheric characteristics important for GCR

It is wellknown that the heliospheric characteristics most important for the GCR propagation in the heliosphere are the SW velocity, the HMF strength and the form of the GHCS [2]. The detailed consideration of behaviour of these characteristics [4] leads to the conclusion that all main HMF and SW features important for GCR:

- the HMF separation into two unipolar hemispheres by the wavy GHCS
- the HMF inversion during sunspot maxima

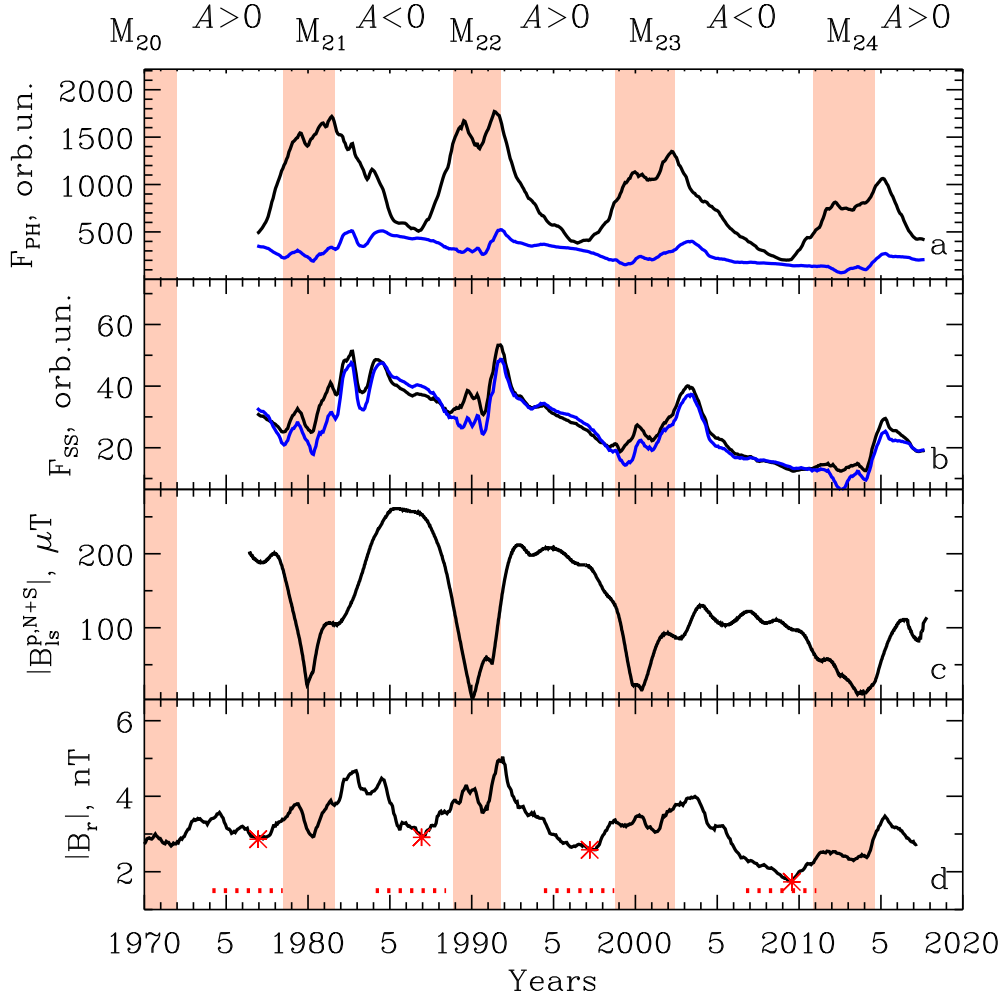


Figure 2. Magnetic field flux through different solar spheres and the poloidal field of the Sun in 1970-2018. All characteristics are 1-year smoothed. Panel a: the SMF flux through the photosphere (dark line) and its part from the dipole SMF (lighter/blue line); b: the same fluxes but through the source surface; c: sum of absolute values of the photospheric SMF line-of-sight components in both polar regions [7]; d: absolute value of the HMF radial component near the Earth [12]. Minimum values B_r^{min} are marked with asterisks, and dotted horizontal lines in Figs. 2 and 3 show the periods when we associate HMF with the poloidal branch of solar activity.

- the strong dependence of SW velocity and hence the HMF azimuthal component on the angular distance from GHCS
- the independence of the HMF radial component on this distance

are due mainly to influence of the poloidal branch of solar activity on SW and HMF distributions in the heliospheric basement. And this influence is very significant: the SW velocity – the main dynamic factor in the heliosphere – changes by a factor of two in the vast volume. The regular HMF changes its direction in phase with the SMF of poloidal branch, and this variation in HMF is no less than that due to the cycle in the toroidal branch.

Now we consider which of two branches of solar activity accounts for the absolute value of $B_r(\vartheta, \varphi)$, constant in each of the unipolar "hemispheres" [5, 9]. Fig. 2 compares the time profiles of the SMF fluxes (both total flux and that due to dipole SMF) through the photosphere (panel a) and the source surface (b) with magnitudes of the line-of-sight-component of the high latitude photospheric SMF (c) and of the absolute value of HMF radial component (d). One can see that the magnetic flux through the photosphere behaves similarly to a toroidal branch (maxima in flux occur during sunspot maxima), and the contribution of the dipole fields is small. On the contrary, the magnetic field flux through a surface source (or an open SMF flux) is significantly shifted in time, its maxima being observed after sunspot maxima, and the contribution of dipole fields is essential.

It can be seen that an open SMF flux correlates well with the HMF radial component, but we believe that the main source of the HMF is different for different years of the periods between the HMF inversions, when the heliosphere is divided by the GHCS into two unipolar hemispheres. We call these periods the HMF dipole phases. In the early years of the HMF dipole phase the HMF characteristics are determined mainly by the decreasing but still large photospheric flux (i.e., the sunspot activity of the toroidal branch), and not the growing but still weak poloidal activity.

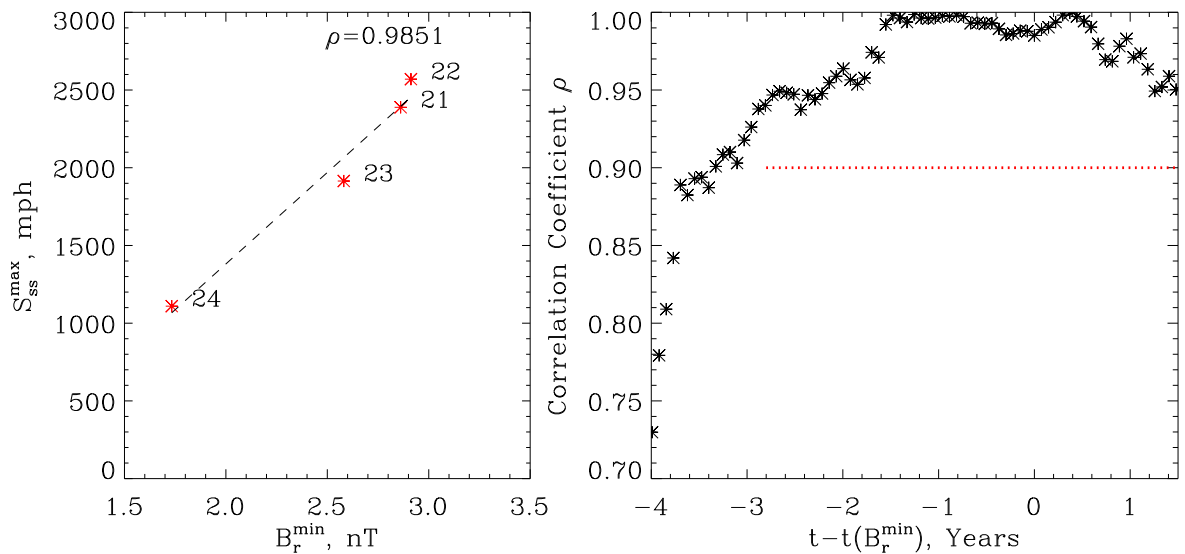


Figure 3. The correlation between the absolute value of the HMF radial components near the Earth in the periods of low sunspot activity and the maximum value of this activity S_{ss}^{max} in the next cycle for solar cycles 21-24. The explanations are in the text. The horizontal dotted lines in this and previous figures show the periods when correlation coefficient ρ is greater than 0.95.

In the second half of the HMF dipole phase the situation is different. Here we use the idea that the characteristics of the poloidal branch of solar activity in minimum of sunspot cycle specify the next maximum of this cycle (see references in [13]). First, we consider the correlation between minimum value of the absolute value of the HMF radial components near the Earth, B_r^{min} , and maximum value of the sunspot area, S_{ss}^{max} , in the next sunspot cycle. Note that we calculated S_{ss}^{max} as the average value of the sunspot areas in two Gnevyshev peaks (see [14]). The left panel of Fig. 3 shows the regression between these characteristics for the last four solar cycles. You can see that correlation is very high. Then we calculate the correlation coefficient between

$|B_r|(t)$ at time t and S_{ss}^{max} and consider how this factor depends on time shift relative to time of minimum $|B_r|$. One can see that in period $t - t(B_r^{min}) \in [-2.5, 1.5]$ (years) the correlation coefficient is very high ($\rho > 0.95$), and before this period it decreases quite sharply. We believe that during this period of high correlation between $|B_r|$ and S_{ss}^{max} the HMF observed near the Earth depends mainly on the characteristics of the poloidal branch of the solar activity.

4. Conclusions

- (i) In the formation and development of the heliospheric characteristics, important for GCR, essential roles are played by both the toroidal branch of solar activity (active regions, sunspots and related phenomena) and poloidal branch (coronal holes, high-latitude magnetic fields, zonal drift of unipolar magnetic field regions etc.), the role of each branch changing with the phase of the solar cycle. Outside the periods of heliospheric magnetic field inversion the poloidal branch of the solar activity forms the global heliospheric current sheet and connected with it distributions of HMF radial component and solar wind velocity. During periods of low sunspot activity the HMF radial component and strength are also the products of the poloidal branch of solar activity.
- (ii) The relatively greater role of the poloidal branch of activity in the heliosphere than on and inside the Sun is due to processes in a layer between them, where the major dynamic factor is the solar magnetic field. As a result, in the transition from photosphere to heliosphere the poloidal solar magnetic fields get the advantage due to its larger scale over the toroidal ones.
- (iii) As a result of the above heliospheric processes, the main observed long-term variation of the GCR intensity, 11-year cycle, as well as the 22-year cycle, are the manifestations of both branches of solar activity, the role of each branch varying with the phase of the solar cycle.

Acknowledgments

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