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Role of the Large-Scale Solar Magnetic Field Structure in the Global Organization of Solar Activity

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Abstract—The relation of the large-scale solar magnetic field structure to the most pronounced manifestations of solar activity (filaments, active regions, sunspots, coronal mass ejections, and coronal holes) has been studied.

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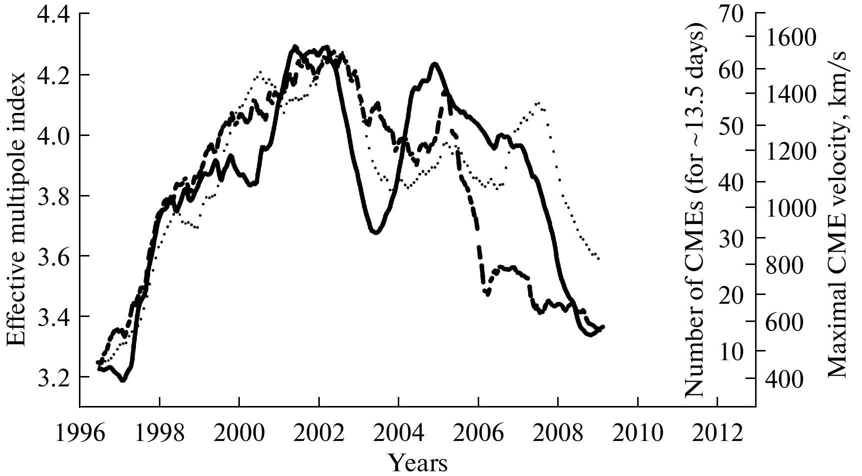
The large-scale solar magnetic field (LSSMF) is a magnetic field with the intensity of several gauss to several dozen gauss (in active regions and corresponding calcium plage areas), which covers almost all of the entire solar surface. A comparison of the LSSMF maps with solar images in the *H* alpha line indicates that these images are in good agreement with one another, which made it possible to study the LSSMF structure based on *H* alpha images up to the beginning of the 20th century (Makarov and Sivaraman, 1989a; Makarov and Sivaraman, 1989b; Obridko and Shelting, 1999). The boundaries of LSSMF structural elements, corresponding to the magnetic field neutral lines, are drawn on images as H alpha filaments and most pronounced active regions. According to (Babcock, 1961; Leighton, 1969), an LSSMF is formed as a result of the diffusion of intense magnetic fields of active regions and sunspots. However, in some studies performed in 1985–1992 (McIntosh and Wilson, 1985; Wilson et al., 1990; Wilson and McIntosh, 1991; Wilson, 1992; Murray and Wilson, 1992), McIntosh and Wilson proposed another LSSMF formation theory based on their own observations and the observations of other researchers. This theory is based on interaction between the global solar magnetic field generated at the bottom of the convection zone and giant convection cells in the solar convection zone. They put forward the following arguments for their theory: (1) LSSMFs are formed before the origination of any significant sunspot groups and almost always exist during all solar cycle phases. (2) New significant sunspot groups originate near existent LSSMF cell boundaries, without distorting the LSSFM structure, and the concentration of these sunspots toward the LSSMF cell boundaries increases with increasing sunspot area. In this case large sunspot groups as a rule originate near areas where the shear is intensified or two different magnetic field fluxes, which are often observed one–two months before the origination of sunspots, merge. (3) When sunspots disappear, their magnetic flux also mostly disappears and does not diffuse over the solar surface. (4) The total sunspot magnetic flux varies by a factor of 10–12 during the 11-year cycle, whereas the flux of large-scale fields increases less than twice; in this case the sunspot total magnetic flux accounts for not more than 11–14% of the total solar magnetic flux. (5) The poleward shift of the LSSMF elements (filaments limiting these elements) is not uniform (i.e., is not diffusion) and differs in different solar cycle phases; discrete jumps of individual LSSMF elements are sometimes observed when these elements move poleward, and the meridional velocity of these elements is as a rule higher than the magnetic field diffusion velocity. According to Arkhypov et al. (2011–2013), LSSMF includes structural elements with average characteristic dimensions of 90°, 180°, 360°, and 24°, corresponding to giant convection cells. The characteristic dimensions of these elements vary during the 11-year solar cycle, decreasing during the growth phase (from the cycle minimum to its maximum) and increasing again during the decline phase (from the maximum to the next minimum).

It has been established that most pronounced solar activity manifestations (active regions, sunspot groups, and flares that occur in these formations) tend to concentrate toward the boundaries of the LSSMF structural elements, which is specifically observed in the formation of the so-called active longitudes (Bumba and Obridko, 1969; Ivanov, 2007). The concentration of these formations (events) toward the boundaries of the LSSMF structural elements (active longitudes and IMF sector boundaries) increases with increasing event intensity (importance) and is most pronounced for rather large and powerful events (for proton and X flares).



Cyclic variations in ESMI (solid line), maximal velocity V_{max} (thick dashed line), and CME occurrence frequency N (thin broken line) during cycle 23.

Superposing the MDI solar magnetic field synoptic maps onto the Stanford LSSMF maps during cycle 23, Ivanov (2012) confirmed that powerful sunspot groups originate near the LSSMF boundaries, and these boundaries originate not less than one–two rotations before the origination of these sunspots. Shelting and Obridko (2001) and Stepanyan et al. (2012) also established that the magnetic field polarity reversal on the surface of a source (including mainly low-order multipoles (dipole and quadrupole) characterizing LSSMF) occurs one–two rotations before the magnetic field polarity reversal on the surface of the photosphere (where higher-order multipoles, corresponding to active regions and sunspots, predominate). The priority of large-scale and global fields was indicated in numerous works by Makarov and coauthors (see, e.g., (Makarov et al., 2001)). Obridko et al. (2011) indicated that precisely the global field is responsible for the position of active regions, and active longitudes are most pronounced in the heliomagnetic coordinate system introduced by the authors. This does not eliminate the evident statement that some background fields can also be formed from the diffusion and drift of sunspot fields.

Obridko et al. (2012) showed that the effective solar multipole index (ESMI), which characterizes the characteristic dimension of LSSMF elements, is closely related to the maximal velocity and occurrence frequency of most powerful coronal mass ejections (CMEs). The ESMI index introduced in (Ivanov et al., 1997), ESMI = –0.5log(Iss/Iph)/log(2.5), characterizes the contribution of different solar magnetic field components (multipoles) and is proportional to a particular average characteristic dimension of the LSSMF structural elements. This characteristic dimension decreases with increasing ESMI. The figure presents cyclic variations in the ESMI (solid line), the maximal velocity V_{max} (thick line), and CME occurrence frequency N (thin broken line) over the entirety of cycle 23. The CME maximal velocity and occurrence frequency were calculated based on data taken from the LASCO list (http://lasco-www.nrl.navy.mil/solwind_transient.list). All ESMI, V_{max}, and N values were calculated at an interval equal to a half of the Carrington rotation (~13.5 days) and were subsequently smoothed over a year.

The Figure indicates that maximal ESMI values correspond to maximal values of the CME velocity (and, correspondingly, energy). When the dimensions of the LSSMF structural elements decrease (ESMI increases), favorable conditions are apparently formed for the combination of large and complex sunspot groups (active regions), which originate near the boundary of these elements, into a unified composite complex including several active regions joined by coronal arc structures. When the characteristic dimensions of the LSSMF structural elements increase (ESMI decreases), such conditions become less favorable. This results in a decrease in the dimensions of these complexes and in the velocity (and, correspondingly, power) of the CMEs originating in them. The complexes, including several active regions and, correspondingly, powerful high-speed CMEs, could not originate at the end of the decline phase (2007–2009), when the characteristic dimensions of the LSSMF structural elements considerably increased. During that period, the maximal velocity of these CMEs was as a rule not higher than 700 km/s. The occurrence frequency of weak low-speed CMEs, originating in individual comparatively small sources (sunspots and erupting filaments), simultaneously relatively increased.

The LSSMF structure is also responsible for the distribution, dimensions, and number of coronal holes in different phases of the 11-year solar cycle and for the corresponding dimensions of high-speed solar wind streams from coronal holes. Wang et al. (1996) and Altschuler et al. (1972) identified coronal holes with areas of the unipolar magnetic field with an open configuration; however, coronal holes almost never completely coincide with the LSSMF elements. The boundaries and dimensions of coronal holes pronouncedly differ depending on the HF spectral lines where they are observed. The position, dimensions, and structure of coronal holes are strongly affected by active regions and sunspots adjacent to coronal holes. The plasma density and temperature within and outside coronal arcs connecting individual elements of active regions and sunspots pronouncedly affect the shape and structure of coronal holes observed in different HF spectral lines. Nevertheless, it is clear that coronal holes are closely related to the LSSMF structure. Tavastsherna and Polyakov (2013) compared coronal holes, which were observed in the He1 10830 Å lines from 1975 to 2003 and in EUV 195 Å from 1996 to 2012, with the solar synoptic maps in the $H\alpha$ line. They found that 70% of coronal holes are observed in the LSSMF elements, the polarity of which coincides with that of the polar magnetic field in the corresponding solar hemisphere. Many authors (Nolte, 1976; Gosling and Pizzo, 1999; Zhang et al., 2002, 2003; McComas and Elliot, 2002; Bromage et al., 2001; Veselovskii et al., 2006; Robbins et al., 2006; Vršnak et al., 2007a, 2007b; Luo et al., 2008; Obridko et al., 2009a, 2009b; Obridko and Shelting, 2011) studied the relation between the solar wind from coronal holes and the dimensions, contrast, and intensity of the magnetic field of the corresponding coronal holes and established an apparent relation between these parameters.

From the above, it follows that the large-scale structure of the solar magnetic field plays the defining role in the global organization of almost all most pronounced solar activity manifestations (active regions, sunspots, filaments, coronal holes, and CMEs).

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