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3D evolution of solar magnetic fields and high-speed solar wind streams near the minimum of solar cycle 23

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Abstract. The numerical method developed by Veselovsky & Ivanov (2006), together with magnetograms of the Sun obtained at the photospheric level were used to calculate the coronal magnetic field with open, closed and intermittent topology during March-December 2007. The results of the modelling are compared with stereoscopic images and movies of the corona observed by EUV telescopes onboard STEREO and SOHO spacecraft. The sources of the permanent and transient high speed solar wind streams as well as the sector structure and the heliospheric plasma sheet observed at the Earth's orbit by the ACE and STEREO spacecraft are discussed.

Keywords. Magnetic field, Solar wind, Solar cycle, Coronal holes.

1. Introduction

The goal of this paper is to present and discuss new observational data during the minimum of solar cycle 23. Available space born telescopic and coronagraph observations onboard the twin STEREO, SOHO and ACE spacecraft helped to find the origins of the high-speed solar wind streams and sector structure of the magnetic field and investigate their dynamics during March–December 2007. In our study we use magnetic field data from Wilcox Solar Observatory and SOLIS for visualization of the three-dimensional structure of the magnetic field within the solar corona. The problem of visualization of three-dimensional magnetic-line patterns in the solar corona is an important part of the more general problem of development of graphical tools for adequate visualization of the magnetic field and more complete information about the state of the near-Sun environment. It is difficult to measure the coronal magnetic field. The lack of such information is usually compensated to some extent by computations. There are many models that can be applied to calculate the magnetic field vector in the solar corona and near-Sun environment from photospheric observations. Models based on potential and force-free approximations are most widely used. There also exist more complete and complicated self-consistent numerical models that describe the joint dynamics of the field and plasma on the basis of magnetohydrodynamic equations. The modern state of the investigations in this field and the difficulties arising during computations are partially reviewed by Aschwanden (2004), Obridko *et al.* (2006), Veselovsky (2002).

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2. A method for visualization of the solar magnetic field

In the present study, we use the coefficients of the spherical harmonic expansion of the solar magnetic field in the potential approximation, which were calculated by G.V. Rudenko from magnetic field data observed at the photospheric level. The method used for extrapolation is described by Rudenko (2001) and the results of the current computations of the harmonic coefficients for certain dates can be found at http://bdm.iszf.irk.ru/. We developed a program that can visualize the field lines derived from these coefficients. This is a convenient tool for visualization of the three-dimensional structure of the magnetic field within the solar corona from its lowest layers to the surface of the solar-wind source. The projection of the field lines onto the skyplane gives important information, which is difficult or even impossible to obtain from the original data in another way. The specific feature of our visualization method is that the magnetic flux density is directly introduced into the computations as an important parameter. The spatial density of the field lines is proportional to the field strength. Thus, in addition to the global pattern of open and closed field lines in the corona, we obtain information about the magnitude and direction of the magnetic field. In Figure 1 closed field lines incoming and outgoing from the photospheric level, are shown in yellow. Open field lines outgoing from the solar surface, that is, lines for which the vector of the magnetic field strength is directed away from the Sun at R = 1, are given in red. Finally, the blue lines correspond to the incoming open field lines. Visualization of the coronal magnetic field works well during the minimum of solar activity in the absence of sporadic perturbations. The results obtained with this method of visualization agree with the observations. The closed magnetic field lines are associated with active regions, the open field lines with coronal holes and high-speed solar wind streams observed onboard ACE.

3. High-speed solar wind streams and magnetic sector observations

High-speed solar wind streams (HSSWSs) and sector structure of the magnetic field observed simultaneously onboard the STEREO, SOHO and ACE spacecraft were used for better understanding of the three-dimensional and time dependent properties of the heliospheric plasma and magnetic field parameters at the Earth's orbit around the minimum of solar activity. We have considered 11 Carrington Rotations (March–December, 2007) during the minimum of solar cycle 23. Sources of HSSWSs with velocities of about 600-700 km/s were the coronal holes which had variable angular spans, geometry and time histories (Veselovsky & Shugay 2008). The four-sector structure of the

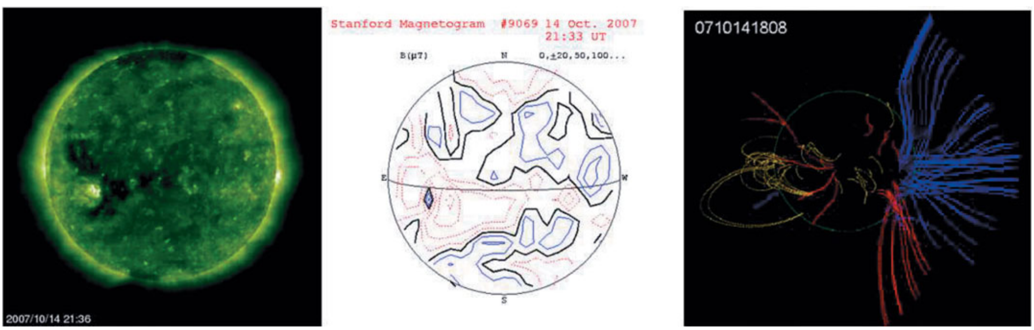

Figure 1. Left panel: the Sun observed by the SOHO/EIT in the Fe XII bandpass (195 Å) on 14 October 2007. Middle panel: Wilcox solar magnetogram for the same day. Right panel: The magnetic field lines in the solar corona according to our calculations.

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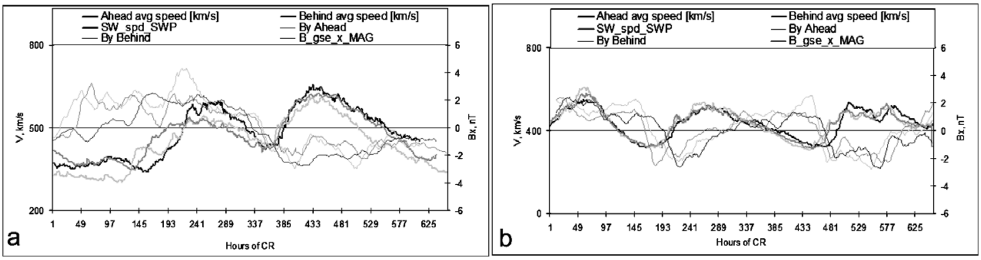

Figure 2. The average value of the interplanetary magnetic field and HSSWSs from three-point observations, ABE (Stereo-A, Stereo-B, ACE) a) The period from March to August 2007 (CR 2054-2058) b) The period from September 2007 to February 2008 (CR2060-CR2064).

interplanetary magnetic field and three HSSWSs were observed during the period from March to August 2007 (CR 2054-2058). Three (or four) coronal holes with different polarity (-+ - +) were the sources of HSSWSs (Fig. 2a). In July-August, 2007 (CR2059) a gradual change from four-sector to two-sector structures of the interplanetary magnetic field took place (−+ +). The two-sector structure of the interplanetary magnetic field (-+) was observed from September 2007 to December 2007 (CR2060-CR2064) (Fig. 2b).Two coronal holes (CH) were the sources of HSSWSs. One of them was a recurrent negative polarity equatorial CH with an active region near/inside it (complex AR+CH) and the other was a recurrent positive polarity middle latitude CH located in the south hemisphere.

4. Summary

We have considered 11 Carrington Rotations (March-December, 2007) during the minimum of solar cycle 23. The method of visualization of the coronal magnetic field works well in a minimum of solar activity in the absence of sporadic perturbations. The global space-time pattern of HSSWSs (600-700 km/s) and their sources can be only partially reconstructed from three-point observations using Stereo-A, Stereo-B, SOHO/EIT and ACE spacecraft. Inclination of the heliospheric current sheet, its shape as well as its position, and the shape and the size of coronal holes determine this pattern in the heliosphere. The geometry of streams appreciably changes from one rotation to another, but preserves the overall zonal and sector structure manifested in the solar wind and the interplanetary magnetic field at the Earth 's orbit.

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