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Evolution of sunspot activity and inversion of the Sun's polar magnetic field in the current cycle

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Abstract

A spatiotemporal analysis of the Sun's magnetic field was carried out to study the polar-field inversion in the current cycle in relation to sunspot activity. The causal relationship between these phenomena was demonstrated in a time-latitude aspect. After decay of long-lived activity complexes their magnetic fields were redistributed into the surrounding photosphere and formed unipolar magnetic regions which were transported to high latitudes. Zones of intense sunspot activity during 2011/2012 produced unipolar magnetic regions of the following polarities, whose poleward drift led to the inversion of the Sun's polar fields at the North and South Poles. At the North Pole the polar field reversal was completed by May 2013. It was demonstrated that mixed magnetic polarities near the North Pole resulted from violations of Joy's law at lower latitudes. Later sunspot activity in the southern hemisphere has led to a delay in magnetic polarity reversal at the South Pole. Thus, the north–south asymmetry of sunspot activity resulted in asynchronous polar field reversal in the current cycle.

Keywords: Solar activity; Sun spots; Solar cycles; Electric and magnetic fields; Solar magnetism

1. Introduction

The Sun's magnetic field exhibits multi-scale and hierarchical behavior. During the 22-year solar cycle the poloidal and toroidal components of the Sun's magnetic field are transformed into each other and interact with magnetic fields of lesser spatial scales. Emerging segments of the Sun's toroidal magnetic field appear at the solar surface as active regions (ARs) composed of magnetic bipoles. According to Joy's law, a typical AR is angled at about 5 degrees, with leading sunspots being closer to the helioequator than following sunspots. Activity complexes (ACs) are composed of interrelated ARs which recur over several solar rotations. As a rule, long-lived ACs are also characterized by positive tilt angles to the solar equator.

After ACs decay, their magnetic fields are redistributed in the surrounding photosphere. According to the empirical concept of Babcock and Leighton, unipolar magnetic regions (UMRs) of following polarities migrate polewards and form the new-cycle polar field while UMRs of leading polarities migrate equatorward (Leighton, 1969). Further development of this concept led to numerical simulations of magnetic flux transport at the Sun's surface due to differential rotation, meridional flows, and supergranular diffusion (Wang et al., 1989; Wang, 2009). Taking into account the magnetic fluxes of ARs and their tilts as the initial conditions, these models reproduced the build-up and reversals of the Sun's polar field (Baumann et al., 2004; Dikpati et al., 2004; Schrijver and Liu, 2008; Jiang et al., 2014).

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Based on the Babcock–Leighton mechanism, the flux transport dynamo improved our understanding of long-term changes in sunspot activity and possible causes of the grand minima (Choudhuri et al., 1995; Choudhuri and Karak, 2009; Karak and Choudhuri, 2011; Olemskoy and Kitchatinov, 2013; Karak et al., 2014). According to the flux transport dynamo, positive tilts of magnetic bipoles initiate a latitudinal divergence of opposite magnetic polarities. Further divergence of opposite polarities results in transformation of the toroidal field to the new-cycle poloidal field. The results of numerical modeling describe the main features of cyclic evolution of the Sun's magnetic fields. Recent analyses of the Sun's zonal magnetic flux revealed its significant north–south asymmetry that has led to an asynchronous polar-field reversal at the Sun's poles (Svalgaard and Kamide, 2013; Mordvinov and Yazev, 2014; Kitchatinov and Khlystova, 2014; Sun et al., 2015).

Here we investigate the further development of the polar-field inversion in the current cycle in more detail. We examined the solar magnetic fields and changes in their zonal structure in causal relation to sunspot activity. Special attention is paid to UMRs of leading magnetic polarities which sometimes migrate polewards. In particular, whether violations of Joy's law are responsible for mixed magnetic polarities near the North Pole in the current cycle.

2. Evolution of the Sun's background magnetic fields in relation to sunspot activity

The current cycle 24 started after a deep and prolonged minimum. Due to the long period of spotless days and weak background magnetic fields (Hoeksema, 2010) it became possible to detect the remnant magnetic fields which formed after the decay of the first ACs (Mordvinov and Yazev, 2014). To study the evolution of the Sun's magnetic fields we analyzed synoptic maps composed of the SOLIS/VSM measurements (Harvey and Worden, 1998). In order to exclude small-scale magnetic fields and measurement errors the original synoptic maps were denoised and smoothed using the walelet decomposition technique.

Synoptic maps show the background magnetic fields over the entire solar surface (in the gray-to-white palette). Fig. 1a shows a wavelet denoised synoptic map for Carrington rotation 2079 (January–February 2009) as an example of magnetic field distribution which is characteristic of the beginning of solar cycle 24. In the very beginning of the current cycle there were no sunspots and the background fields were very weak and fragmentary. Negative polarity dominated near the North Pole, while positive polarity dominated at the South Pole.

As the cycle progressed, ACs appeared. At the beginning of the current cycle, sunspot activity prevailed in the northern hemisphere. After decay of the first ACs, their magnetic fields dispersed into the surrounding photosphere and formed UMRs of following (positive) polarity. A causal relation between ACs, their remnant magnetic fields and high-latitude UMRs is evident at the beginning of the current cycle. The second synoptic map in Fig. 1(b) shows magnetic fields at the phase of activity rise (CR 2102 occurred in October 2010). To study the background magnetic fields in relation to recurrent ACs we superimposed strong preceding magnetic fields on the weak magnetic fields. Strong fields (above 200 G in modulus) are summarized over CRs 2094–2102, thus the black spots in Fig. 1(b) show long-lived ACs which had existed in the course of CR 2102 and during the time interval of nine CRs preceding CR 2102.

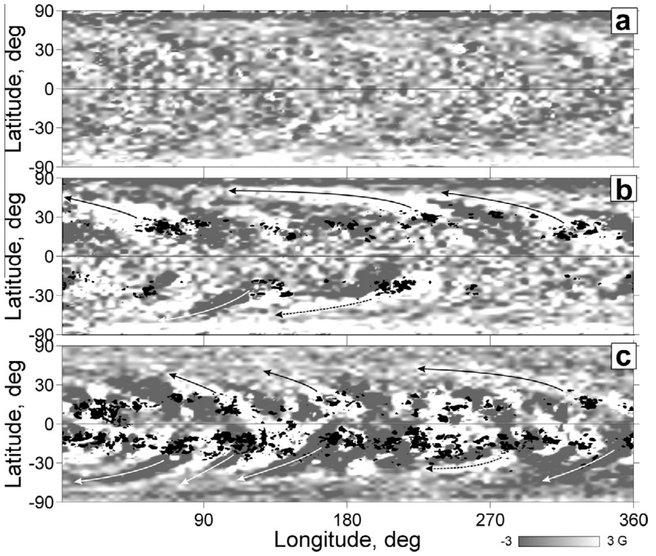

Fig. 1. Synoptic maps of solar magnetic fields for CRs 2079 (a), 2102 (b), and 2149 (c) are shown in the gray-to-white palette. Magnetic fields (>200 G in modulus) are shown in black. These are superimposed on given synoptic maps from the nine preceding CRs. The solid/dashed arrows show UMRs of following/leading polarities.

The black and white arrows indicate UMRs of positive and negative polarities whose evolution is determined by the Sun's differential rotation and the meridional flows. UMRs of predominantly following polarities are transported polewards. Sometimes UMRs of leading polarities are also transported to higher latitudes. For example, the most extended UMR of positive (leading) polarity in the southern hemisphere stretched over latitudes −10° to −70° within longitudes 225–115°. This UMR is marked by a dashed arrow in Fig. 1(b). The reason for such anomalies will be discussed below.

In 2013 zonally averaged magnetic flux demonstrated short-term changes and polarity alternations at the North Pole. These fluctuations resulted from highly mixed magnetic polarities in the northern polar zone. Some ambiguity in the polar flux behavior was also caused by the annual change in the pole seeing conditions due to the Earth's excursions relative to the helioequator. Taking into account this ambiguity, it was concluded that the zonally averaged magnetic flux at the North Pole reversed its sign by May 2013 (Mordvinov and Yazev, 2014).