On the Polar Field Distribution as Observed by SOLIS

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Abstract. We use Vector Spectromagnetograph (VSM) chromospheric full-disk magnetograms, from the Synoptic Optical Long-term Investigations of the Sun (SOLIS) project, to study the distribution of magnetic field flux concentrations within the polar caps. We find that magnetic flux elements preferentially appear toward lower latitudes within the polar caps away from the poles. This has implications on numerous solar phenomena such as the formation and evolution of fine polar coronal structures (i.e., polar plumes). Our results also have implications for the processes carrying the magnetic flux from low to high latitudes (e.g., meridional circulation).

1. Introduction

Near minima of the activity cycle of the Sun, solar poles are characterized by unipolar magnetic dominated areas, in particular at photospheric heights (Babcock & Livingston 1958; Babcock 1959; Howard 1972; Timothy, Krieger, & Vaiana 1975; Harvey, Harvey, & Sheeley 1982; Varsik, Wilson, & Li 1999). The so-called “polar caps” are quite prominent features due to their large sizes and their continuous presence through the solar cycle. They are the counterpart of the coronal polar holes where the fast solar wind streams (Schwenn, Muelhaeuser, & Rosenbauer 1979) and plasma heating (Schatzman 1949; Osterbrock 1961) originate. The physical processes laying behind these phenomena are still far from being completely understood. A significant portion of the mostly unipolar magnetic flux opens increasingly with height and fills most the heliosphere that contributes to the formation of the heliospheric magnetic field.

The solar polar caps are not sufficiently studied for different reasons (observational and modeling). In addition to the important projection effects due to the solar geometry and the lack of off-ecliptic-plane observational facilities of the magnetic field, the latter is intrinsically weak close to the solar poles (Grigor’ev 1988; Bogart, Hoeksema, & Scherrer 1992; Varsik, Wilson, & Li 1999; Varsik et al. 2002). In addition, the solar poles are only partially observable from the ecliptic plane due to $B_0$. However, instrumental limitations in matter of sensitivity are the major problem for accurately measuring and studying the solar fields.

Complex dynamics in the solar upper convection zone together with other dynamical phenomena (e.g., differential rotation), magnetic fields of decaying active regions drift monotonously to form the large-scale field observed on the solar surface, in particular the polar caps (see Leighton 1964; DeVore & Sheeley 1987; Sheeley, Nash, & Wang 1987; Bilenko 2002). The same processes
contributes significantly to the so-called polar magnetic reversal (Babcock & Babcock 1955) that is the change of the dominant magnetic polarity to the opposite from a solar cycle to the following one (Bilenko 2002). Under the effect of solar differential rotation, supergranular diffusion and meridional circulation, the poleward migration of the active region trailing polarities (in relative excess due to the diffusion of the leading polarity of emerging bipolar regions near solar minimum across the solar equator as suggested by Wang, Nash, & Sheeley 1989) has been suggested to be responsible of the reversal of the magnetic polarity of the solar poles (e.g., Babcock & Babcock 1955; Babcock 1961; Leighton 1964). Meridional flows has been observed and identified as the main process of flux transport from low to upper latitudes (Howard 1974; Duvall 1979; Cameron & Hopkins 1998; Snodgrass & Dailey 1996; Durrant, Turner, & Wilson 2004) through helioseismology and magnetic tracers (Duvall 1979; LaBonte & Howard 1982; Ulrich et al. 1988; Howard & LaBonte 1981; Topka et al. 1982; Wang, Nash, & Sheeley 1989). The weak flow, of few times $10 \text{ m s}^{-1}$ at best, can be measured only to mid solar latitudes since the techniques used fails above roughly $45^\circ - 50^\circ$. However, it is of capital importance to obtain additional constraints on these flows up to high latitudes close to the solar poles. This would be of great use for models dealing with flux transport and the solar dynamo.

Raouafi, Harvey, & Solanki (2006a,b; 2007) studied the plasma dynamic properties in the coronal polar plumes by means of forward modeling. They found that modeled spectroscopic emissions from polar coronal plumes rooted close to the solar poles do not match the observed coronal spectra by the Ultra-Violet Coronagraph Spectrometer (UVCS; Kohl et al. 1995) on board the Solar and Heliospheric Observatory (SOHO; Domingo, Fleck, & Poland 1995). They speculated that polar plumes would preferentially be based within the polar holes about $10^\circ$ away from the solar poles. It is well known from previous studies that polar plumes are the product of magnetic reconnection of a relatively large unipolar flux element with an emerging opposite polarity. Thus, the study of the polar magnetic flux distribution would yield insights and clues about the distribution of the coronal structures, such as polar plumes. In the present paper, we confirm Raouafi, Harvey, & Solanki’s results through the study of the polar flux distribution as a function of latitude and suggest the probable effects on solar phenomena that are at the origin of such a distribution.

Saito (1958) used eclipse observations and found a similar distribution of the so-called “polar rays”.

2. OBSERVATIONS AND DATA ANALYSIS

The magnetic line-of-sight (LOS) component obtained from the polarization of photospheric lines is not sufficiently strong and does not allow to study accurately the distribution of magnetic flux near the poles. In addition, the transverse field measurements are not sufficiently sensitive. These make the task of addressing polar fields from photospheric magnetograms rather difficult. However, LOS-magnetograms obtained from chromospheric lines (e.g., Ca II 854.2 nm) benefit from the canopy structure of the magnetic field which yield strong signals to the solar limb (see Figure 1). It is noteworthy that the photospheric LOS-magnetograms from the same instrument are of equally good
The chromospheric (Ca $\text{ii}$ 8542 Å) LOS-magnetograms from SOLIS-VSM are utilized to study the latitude distribution of the unsigned magnetic flux in the polar regions. We are interested in the distribution of magnetic flux elements regardless of their polarities. In addition, polar caps are typically dominated by one polarity each which also justifies the use of unsigned magnetograms. The opposite polarity in these areas contributes little to the total flux and is represented by relatively small-diffuse flux elements.

The non-uniform visibility across the solar disk is corrected for assuming an East-West uniform distribution of magnetic flux elements when a considerable number of magnetograms are averaged. This is more reliable for quiet sun regions. The correction is dependent on the distance to disk center and is represented by

$$f = C_0 \left( \frac{r}{R_\odot} \right)^n + 1,$$

where $C_0$ is an adjustable parameter and is found to be nearly equal to 1.1 and $r$ is the distance to disk center. This empirical correction enhances magnetic fields close the solar limb that are relatively noisy. By setting all magnetic fields with strength below a given threshold, that is equal to 5 Gauss in the present case, to zero, the noise effect is reduced significantly. In addition, thresholding the magnetograms allow for the boundaries of magnetic flux elements to be easily defined.

A size and shape dependent recognition methods of closed structures is used to identify and locate the flux elements. The method dependence on the size and shape of flux elements allows for studying the distribution of different population of magnetic structures. Figure 2 illustrates how the used method
for the selection of magnetic elements works with a size threshold of $5 \times 3$ pixels (1 pixel $\approx$ 1.13 arcsec). Note that magnetic elements with smaller sizes are not selected. The distribution of the selected elements as a function of latitude is obtained by determining the an average location for every selected feature. However, the obtained distribution is absolute and might be biased by the latitude area dependence. In order to stay clear of that, the obtained distribution are normalized by the latitude area distribution taking into account the solar geometry (i.e., $B_0$ angle). Since single histograms do not show clearly the distribution of magnetic flux elements due to statistical reasons, they are monthly averaged.

3. RESULTS AND DISCUSSION

Figure 3 displays the monthly averaged distributions of magnetic flux for the north polar cap as a function of latitude from September till December 2006. The different curves are indexed accordingly in the same figure and the average of the obtained monthly histograms is given by the grey dashed line. The approximately horizontal and oblique straight lines are linear fits of portions of the latter for latitudes ranging from $55^\circ - 73^\circ$ and $74^\circ - 90^\circ$, respectively. These distributions are obtained by imposing a minimum size of $5 \times 3$ pixel as shown by Figure 2.

The linear fits show that the distribution density of polar flux elements normalized by the surface area is relatively uniform at low latitudes up to approximately $70^\circ - 75^\circ$. At higher latitudes this density has a decreasing trend toward the solar pole. It is clear from curves that the decrease is persistent and from the linear fit that it is significant although few peaks shows up very close to the pole (see the September curve for instance). This suggests that flux elements, in particular relatively large ones (see Raouafi, Harvey, & Henney 2007), are more concentrated at low latitudes rather than higher latitude elements within the polar cap.

The flux distribution as a function of latitude has an impact on numerous solar phenomena such the location of fine coronal polar structures. Raouafi, Harvey, & Solanki (2007) built different numerical models to study the plasma...
Polar Field Distribution

Figure 3. Monthly averaged histograms of the magnetic flux distribution for features larger than $5 \times 3$ pixel as a function of latitude for the north polar cap. The grey dashed curve is the average of the four previous ones. The straight lines are linear fits for portions of the grey dashed curves for latitudes ranging from $55^\circ - 73^\circ$ and $74^\circ - 90^\circ$.

dynamics in polar plumes. In all these models, that cover almost all the possible cases for the outflow velocity and turbulence of the plasma, they found that polar plumes rooted close to the pole are found to have spectral signatures that are not observed in the solar corona. They concluded that polar plumes would preferentially be rooted more that about $10^\circ$ from the pole. There is also observational evidence that the base of polar plumes, in particular bright ones, are relatively large magnetic flux areas dominated by one polarity (Saito & Tanaka (1957a,b); Harvey 1965; Newkirk & Harvey 1968; Lindblom 1990; Allen 1994). The latter and Raouafi, Harvey, & Solanki’s findings would agree well with the picture we are drawing here on the density distribution of magnetic flux on the polar caps. This is more evident in the case where we consider relatively large flux elements.

The results of the present study are of capital importance for solar phenomena that are inaccurately determined at high latitudes, such as meridional circulation. Meridional flows are widely believed to be one of the main factors causing the inversion of the magnetic polarity of the poles from one solar cycle to the next. Together with supergranular diffusion, meridional flows bring the magnetic flux of decaying active regions from low to high latitudes causing then the well known polar magnetic reversal. Due to the flow signal weakness in Doppler measurements (Zhao & Kosovichev 2004; Haber et al. 2002) it is not well understood how this phenomenon operates at high latitudes and in particular close to the poles. The density distribution of the unsigned magnetic flux at the polar regions reported on here suggests that the mechanisms responsible for the flux transport greatly diminish before reaching the poles. Such results
would be of great importance for models dealing with flux transport and the solar dynamo.

4. CONCLUSION

We studied the distribution of magnetic flux elements as a function of latitude near solar minimum of activity utilizing LOS-magnetograms from the SOLIS-VSM magnetograph. Chromospheric magnetograms are preferred to photospheric ones because of the better signal in the LOS magnetic component due the canopy structure of the magnetic field. Additional effects, such as the seething in the horizontal photospheric magnetic fields, are avoided by using chromospheric magnetograms. The magnetic data is recorded almost daily from September through December 2006. The north pole data was chosen for two reasons:

- the north polar cap was better developed than the southern one during this period of time;
- the north pole was more visible than the southern one ($B_0 > 0$).

A recognition method of closed structures has been used to select magnetic flux elements. Thresholds on size and shape of the elements to be selected are tunable parameters of the method. The average spherical coordinates (latitude and longitude) of the selected elements are computed and their daily latitudinal distributions are determined. In order to remove any effect of the surface area of the polar cap, the histograms are normalized with respect to the area corresponding to each latitude bin taking into account the different solar geometrical parameters for the each magnetogram. Since daily distributions do not reflect the real density of magnetic elements for statistical reasons, monthly averages of the normalized histograms are then computed.

The density of the unsigned magnetic flux elements within the polar magnetic cap (normalized by the surface area of the polar cap) is found to be strongly dependent on solar latitude. Flux elements are found relatively uniformly dense up to latitudes of about 75° – 80° followed by a significant decrease in their latitudinal distribution at higher latitudes close to the solar pole. Although, a difference in the distribution of relatively small and large flux elements is found, the density decreasing behavior toward the pole is found in all the data considered (for details see Raouafi, Harvey, & Henney 2007). We believe that the mechanisms responsible for the transport of the magnetic flux of low latitude decaying active regions toward high polar latitudes are less efficient close to the poles. This means that the meridional circulation responsible for the flux transport slows before reaching the poles. Such a result would have a significant impact on the theories and models dealing with flux transport. These results also put important constraints on solar phenomena that are inaccurately (if at all) determined by other means, such as helioseismic studies that become inefficient at high latitudes.

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