Solar and Stellar Magnetic Fields: Origins and Manifestations
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Solar Open Magnetic Flux Migration Pattern over Solar Cycles

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Abstract. The objective of this study is to investigate the solar-cycle variation of the areas of solar open magnetic flux regions at different latitudes. The data used in this study are the radial-field synoptic maps from Wilcox Solar Observatory from May 1970 to December 2014, which covers 3.5 solar cycles. Our results reveal a pole-to-pole trans-equatorial migration pattern for both inward and outward open magnetic fluxes. The pattern consists of the open flux regions migrating across the equator, the regions generated at low latitude and migrating poleward, and the regions locally generated at polar regions. The results also indicate the destruction of open flux regions during the migration from pole to equator, and at low latitude regions. The results have been published in Scientific Reports (Huang *et al.* 2017)

Keywords. Sun: activity, Sun: corona, Sun: magnetic fields

1. Introduction

How and why the solar magnetic fields change polarity every 11 years is still not fully understood. Coronal holes are the regions with "open" magnetic fields, which are the fields with field lines extending far away from the Sun. Such fields are the largest-scale global magnetic fields of the Sun. Therefore, coronal holes are good tracers for the change of global solar magnetic field, and many studies have examined the variations of different properties of the coronal holes (e.g., Obridko & Shelting 1999, Bilenko 2002, Hess Webber *et al.* 2014, Karna *et al.* 2014, Karachik *et al.* 2010, Bilenko & Tavastshema 2016). In this study, we identify the coronal holes as the open magnetic flux (OMF) regions, and examine the temporal and spatial variations of the area and magnetic polarities of the open magnetic flux regions over three and half solar cycles from 1976 to 2014.

2. Identification of coronal holes

We use the radial-field synoptic maps from the Wilcox Solar Observatory (WSO) from May 1976 to December 2014, corresponding to Carrington rotation number 1642 to 2158, for this work. To identify the regions with open magnetic fields, we first applied the Potential Field Source Surface model (Schatten *et al.* 1969) to construct the three-dimensional magnetic field between the solar surface and an upper boundary (source surface), where all field lines are assumed to have become radial. The source surface is placed at $2.5R_{\odot}$ from the solar center, following earlier studies (Obridko & Shelting 1999, Wang & Sheeley 1990). Next, the magnetic field lines are traced from the source surface to the solar surface, and the footpoints of open field lines are identified as the OMF regions.

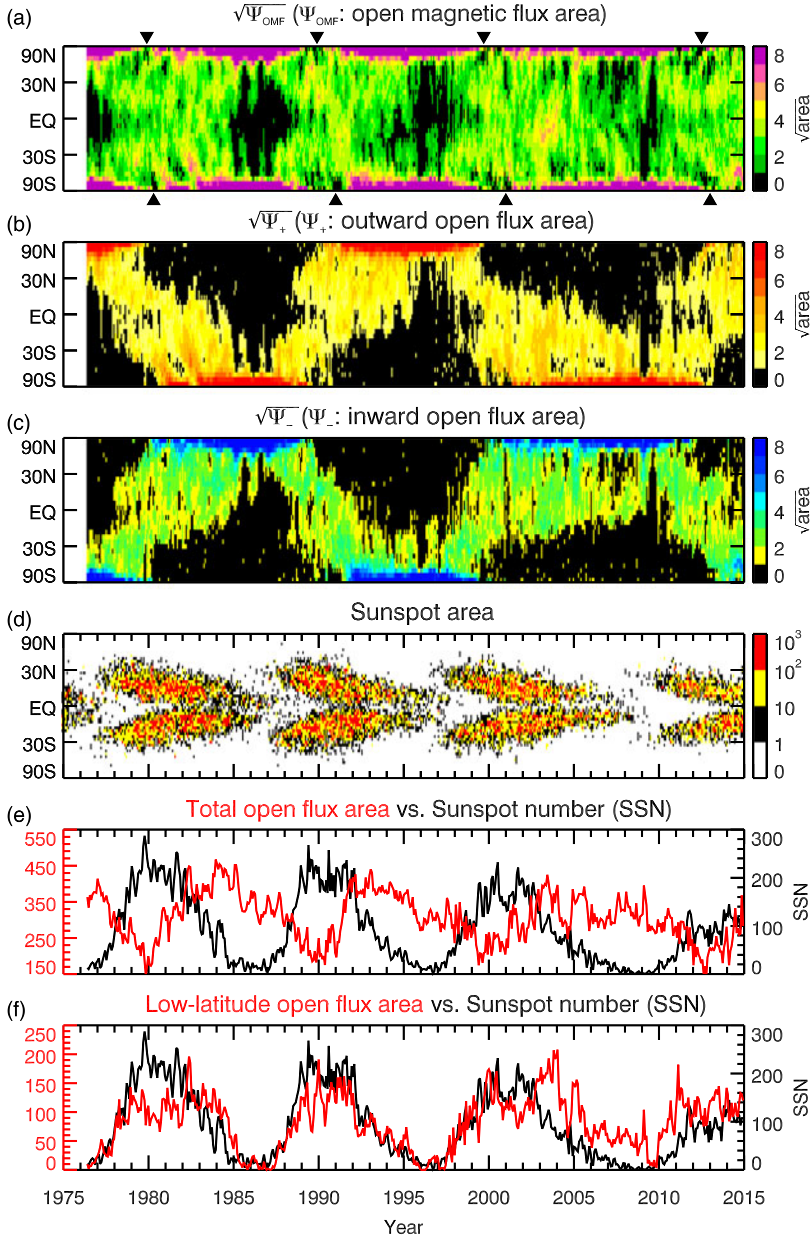

Figure 1. The upper three panels are the time maps of (a) unsigned OMF; (b) outward OMF; (c) inward OMF. Panel (d) shows the time map of sunspot areas. Panel (e) and (f) compare the total sunspot number (black line) with the total open flux area and the low-latitude open flux area, respectively. (adapted from Huang *et al.* 2017)

3. Solar cycle variation of coronal holes

The time maps of outward (Ψ_+), inward (Ψ_-), and unsigned OMF ($\Psi_{\rm OMF} = \Psi_+ + \Psi_-$) areas are plotted in the upper three panels in Fig 1 (adapted from Huang *et al.* 2017). As a comparison, we also constructed the time map of sunspot area by using the data from the Royal Greenwich Observatory. The sunspot area map is placed in Fig 1(d).

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Figure 1(a) shows that the variation of OMF area is approximately symmetric at the two poles. Fig. 1(b) and (c) reveals that the outward and inward fluxes are mostly concentrated in the opposite polar regions during the quiet period, spread to lower latitude during the rising phase of solar activity, cross the equator around the solar maximum, and reach the opposite pole during the decreasing phase of sunspot number, leading to the polarity reversal in the two hemispheres. The average migration rate estimated from the plots is $\approx 10.3 \pm 2.5$m s^{-1}, slightly slower than the surface poleward meridional flow speed ($\approx 15 - 20$ m s^{-1}). The temporal variations of the OMF areas are compared with that of the sunspot number in panels (e) and (f). The comparison shows that the total OMF area is negatively correlated with the sunspot number while the low-latitude OMF area is positively correlated with the sunspot number.

The cause for the pole-to-pole trans-equatorial (PPTE) pattern of the OMF regions is investigated by comparing the total areas within different latitude ranges during the evolution of a solar cycle. The analysis indicates that the PPTE pattern consists of four components: (1) majority of the polar open fluxes are locally generated in the polar regions; (2) some open flux regions are locally generated and dissipated without migrating to higher latitudes; (3) some open flux regions migrate across the equator; (4) some open flux regions migrate to higher latitudes.

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