SPATIAL-TEMPORAL STRUCTURE AND DISTRIBUTION OF THE SOLAR PHOTOSPHERIC MAGNETIC FIELD

TIBEBU GETACHEW

University of Oulu Graduate School
Space Climate Research Unit
Faculty of Science
University of Oulu
Finland

Academic Dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public discussion in the Auditorium L10, Linnanmaa, on November 8th, 2019, at 12 o’clock noon.
Opponent
Prof. Lidia van Driel-Gesztelyi, Mullard Space Science Laboratory, University College London, UK

Custos
Prof. Kalevi Mursula, University of Oulu, Finland

Pre-examiners
Prof. Roman Brajša, Hvar Observatory, Faculty of Geodesy, University of Zagreb, Croatia
Dr. J. Todd Hoeksema, W.W. Hansen Experimental Physics Lab., Stanford University, USA

Supervisors
Prof. Kalevi Mursula, University of Oulu, Finland
Doc. Ilpo Virtanen, University of Oulu, Finland

ISBN 978-952-62-2436-7 (PDF)
ISSN 1239-4327

Punamusta Oy 2019
Tibebu Getachew,

Spatial-temporal structure and distribution of the solar photospheric magnetic field
Space Climate Research Unit, University of Oulu, Finland
Report No. 132 (2019)

Abstract

I have made a detailed study of the fundamental properties of the solar photospheric magnetic field, which helps in better understanding the Sun’s radiative and particle outputs that affect the Earth’s near-space environment, as well as the entire heliosphere. Photospheric magnetic field is an essential parameter for space weather and space climate. The photospheric magnetic field includes a wide range of large-scale and small-scale structures, but the contribution of weak, small-scale fields to the total flux on the solar surface is dominant.

This thesis discusses the spatial-temporal structure and long-term evolution of the solar photospheric magnetic field. Particularly, the thesis presents, for the first time, the spatial distribution of the asymmetry of weak field values and its evolution in solar cycles 21-24. I found that the asymmetry (also called shift) of the distribution of positive and negative weak-field values is a real physical phenomenon. I also found that the shifts are most effectively produced at the supergranulation scale.

I studied the asymmetry of the distribution of weak field values separately in the two solar hemispheres. My results show that the shifts of weak-field field distributions in the two solar hemispheres have always the same sign as the new polarity of the polar field in the respective hemisphere and solar cycle. I also found that the hemispheric shifts change their sign in the late ascending to maximum phase of the solar cycle and attain their maximum in the early to mid-declining phase. This evolution of the hemispheric weak-field gives a new signal of the solar magnetic cycle.

We also studied the long-term spatial-temporal evolution of the weak-field shift and skewness of the distribution of photospheric magnetic field values during solar cycles 21-24 in order to clarify the role and relation of the weak field values to the overall magnetic field evolution. Our results give evidence for the preference of even the weakest field elements toward the prevailing magnetic polarity since the emergence of an active region, and for a systematic coalescence of stronger magnetic fields of opposite polarity to produce weak fields during the poleward drift of the surge.

Keywords: Photospheric magnetic field, solar activity, Space climate
Preface

This work has been carried out in the Space Climate research unit of the University of Oulu. The work has been conducted as part of ReSoLVE (Research on Solar Long-term Variability and Effects) Centre of Excellence and fully funded by the Academy of Finland.

First of all, I would like to thank my supervisors Prof. Kalevi Mursula and Doc. Ilpo Virtanen, for giving me the opportunity to work with them and for their patience guidance, expertise, encouragement and advice throughout this process.

I would also like to thank all members of the Space Climate research unit, especially Timo A., Amr, Jennimari, Pauli, Lauri, Antti, Iiro and Timo Q., for their support, friendship and company throughout this process. Thank you Alexander, Pauli and Abiyot for arranging great trips to Mount Wilson and Griffith Observatories, and also other wonderful locations in Los Angeles during the COSPAR 2018 Scientific Assembly. Thank you all my friends for your wonderful friendship.

Last but not least, I will forever be grateful to my family in Ethiopia: my father, mother, brothers, sisters and wife for their unconditional love and support throughout my life.

Oulu, October 15, 2019

Tibebu Getachew
Original publications

This thesis consists of an introduction and the following four original papers:


In the text, original papers are referred to using roman numerals I–IV.

The author performed the data analysis for all papers. He was also the first author in Papers I, II and III, and contributed essentially to Paper IV.
Contents

Abstract
Preface
Original publications
Contents
1. Introduction .................................................. 9
2. The Sun ....................................................... 11
  2.1. Solar interior .......................................... 11
  2.2. Solar atmosphere .................................... 12
  2.3. Solar granulation .................................... 13
3. Solar wind ................................................... 16
  3.1. Solar wind properties ............................... 17
  3.2. Types of solar wind ................................ 17
  3.3. Heliospheric magnetic field ...................... 17
  3.4. Heliospheric current sheet ...................... 18
4. Solar cycle .................................................. 22
  4.1. Sunspot butterfly diagram ......................... 23
  4.2. Hemispheric sunspot number ...................... 23
5. Evolution of the large-scale photospheric magnetic field .............. 26
  5.1. Magnetic dynamo and the Hale cycle ............ 26
  5.2. Properties of bipolar magnetic regions .......... 29
  5.3. Decaying active regions ......................... 30
  5.4. Photospheric Hale boundary ..................... 32
  5.5. Polar region fields ................................ 34
  5.6. Unipolar fields opening up to the heliosphere 35
6. Evolution of the quiet-Sun photospheric magnetic field .............. 38
  6.1. Granular magnetic fields ......................... 39
  6.2. Internetwork fields ................................ 41
  6.3. Network fields ..................................... 41
  6.4. Ephemeral Regions ................................ 42
  6.5. Extended solar cycle .............................. 42
7. Asymmetry of the photospheric magnetic flux ........................ 45
  7.1. Distribution of the signed photospheric magnetic field values 47
7.2. Distribution of the signed weak-field values ................. 48
  7.2.1. Asymmetric distribution of signed weak fields values .... 48
  7.2.2. Weak field shift and spatial scale ....................... 50
  7.2.3. Weak field shift of several data-sets ................... 51
  7.2.4. Weak field shift and fitting ranges ..................... 51
7.3. Hemispheric weak-field shifts .............................. 52
8. Summary and conclusion ........................................... 56
References ............................................................ 58
1. Introduction

Human life on Earth is dependent on the Sun, as it gives most of the energy needed to form the conditions on the Earth appropriate for life. Several written records and chronicles have shown that the Sun is one of the most important celestial objects forming the genesis for philosophy and civilization during the ancient times. Human knowledge and understanding of the Sun have evolved with time. In ancient times human exploration of space has led to the foundation for the development of instrumentation capable of detecting the unknown beyond the Earth.

After a major development in the early seventeenth century, the invention of the telescope, astronomers turned their telescopes toward the Sun, and reported the existence of black spots (now called sunspots) on the solar disc. In the mid-nineteenth century, the German amateur astronomer Samuel Heinrich Schwabe [Schwabe, 1849] showed the periodic nature of the sunspot activity in an 11-year cycle, called the solar cycle (also called the Schwabe cycle). Another fundamental discovery in solar physics history in the mid-nineteenth century was the observation of a huge solar flare (also called the Carrington flare) by Richard Christopher Carrington [Carrington, 1859] and Richard Hodgson [Hodgson, 1859] on September 1, 1859 followed by a disturbance of the Earth’s magnetic field (a geomagnetic storm) about 17 hours later. This was the first documented space weather event that connects a solar event to a geomagnetic event [Cliver and Svalgaard, 2004].

Although fairly systematic sunspot observations had continued until then for about three centuries by several observers, it was only in the early twentieth century that the magnetic property of sunspots was detected. The discovery of the effect of a magnetic field on spectral lines (the Zeeman effect) by Pieter Zeeman [Zeeman, 1897] was of particular importance for the development of modern physics [del Toro Iniesta, 1996]. Using the Zeeman effect, George Ellery Hale [Hale, 1908] was the first who detected that sunspots are locations of strong magnetic fields. Hale [1924] subsequently found that sunspots in the two solar hemispheres had oppositely ordered magnetic polarities and that the sign of the magnetic field in each hemisphere undergoes a complete cycle every 22 years (now called Hale cycle), twice the length of the sunspot cycle. Soon after the discovery of magnetic
fields in sunspots, the magnetic property of the non-spot regions of the Sun has also become evident. This thesis presents the spatial-temporal evolution of the small- and large-scale photospheric magnetic fields that partly opens up to the heliosphere.
2. The Sun

2.1. Solar interior

The Sun has a mass of approximately $2 \times 10^{30}$ kg, which is approximately 330000 times the mass of the Earth. The solar radius is $6.96 \times 10^8$ m (approximately 109 times the radius of the Earth). Its surface area is $6.1 \times 10^{18}$ m$^2$ (11900 times that of the Earth) and volume is approximately $1.4 \times 10^{27}$ m$^3$ (1.3 $\times 10^6$ times that of the Earth). It is composed of hydrogen (approximately 90%), helium (approximately 10%) and other heavier elements (approximately 1%). The temperature of the Sun’s surface is about 5800 K which is sixteen times hotter than boiling water. The age of the Sun is 4.57 billion years.

The solar interior which is illustrated in the upper half of Figure 2.1 has three major layers, the core, the radiative layer and the convective layer. The core spans from the center to about 25% of the solar radius. This layer has a temperature (at the very center) of about $1.6 \times 10^7$ K. The Sun’s energy is generated in the core by thermonuclear fusion.

The radiative layer encompasses 45% of the solar radius. Both in the core and radiative layers the energy is transported outward in the form of radiation. The convective layer forms the outermost layer of the solar interior and has a thickness of 30% of solar radius. In this region the energy is transported by convection (fluid motions) driven by thermal buoyancy. The convection zone is like a layer of fluid heated strongly from below where warm liquid rises up, cools down and subsides down again. These rising and subsiding flows form convection cells in the convection layer.
2.2. Solar atmosphere

The solar atmosphere (from the solar surface to the Sun’s upper atmosphere) consists of four layers, the photosphere, chromosphere, transition region, and corona. The photosphere is the visible solar surface and vertically spans up to 500 km of the solar atmosphere. The temperature of the photosphere decreases from about 6000 K at the bottom of the photosphere to about 4000 K at the outermost part of the photosphere. Most of the light we receive from the Sun originates in the photosphere and hence most of the information we have about the Sun mainly originates from this layer. The magnetic nature of the photosphere, which is the main topic of this thesis, will be discussed later in Chapters 5-7.

Above the photosphere is the chromosphere which extends up to about 2000 km. At the upper end of the chromosphere the temperature begins to rise rapidly. Above the chromosphere there is a thin transition region (thickness about 500 km) where the temperature increases from $10^4$ K to coronal temperatures of the order of $10^6$ K.

The corona is the outermost part of the solar atmosphere which expands into the planetary space and forms the heliosphere. Solar corona consists of hot, rarified plasma immersed in the magnetic field emanating from the solar photosphere.
The corona spans from the transition region to the height where the solar wind is accelerated, a few solar radii above the photosphere.

Total solar eclipse is a natural laboratory to view the faint solar corona, as most of the light information from the solar disk is blocked during that time. Figure 2.2 shows an example of white-light image of the solar corona taken on solar eclipse of 11 July, 2010. As can be seen in Figure 2.2, the solar corona is permeated with closed (rooted to the underlying photosphere at two ends) and open magnetic fields (rooted to the photosphere at only one end and extending out to the heliosphere).

Figure 2.3 shows an example of UV/X-ray observations of the solar corona. Open magnetic field regions have a low plasma density in the corona and are sources of fast solar wind streams. They appear as dark patches in UV and X-ray images like in Figure 2.3. These regions are commonly called coronal holes. On the other hand, closed magnetic field line regions have enhanced emissions and appear bright in UV and X-rays, with the most clearly visible being bright active regions (ARs).

### 2.3. Solar granulation

The convective material rising from the Sun’s interior overshoots into the solar atmosphere, which is stable against thermal convection. Since the density of the solar atmosphere decreases with height, after passing a distance comparable to the density scale height, the overshoot convective material expands horizontally
and cools down and turns over to form intergranular lanes (darker intermediate lines between granules) of down flowing material. As a result, a granular structure consisting of rising warmer gas in the centers of the granules and descending cooler gas in the intergranular lanes is observed on the solar (photospheric) surface (see left panel of Figure 2.4). Typical horizontal length scales (diameters) of granular cells range approximately from 0.5-2 Mm (Mm=10^6 m) and typical lifetimes from 5-10 minutes.

A larger structure of granular cells called supergranulation is also evident on the solar surface. Supergranular cells have a typical diameter of 30-35 Mm and lifetime of about 24 hours [Rincon and Rieutord, 2018]. The existence of supergranulation was detected by Hart [1954] and later recognized and named by Leighton et al. [1962]. The right panel of Figure 2.4 shows the Doppler image of the solar disc, depicting supergranulation with areas moving toward us appearing dark, and areas moving away, bright.

Shortly after the detection of supergranules, the existence of giant convection cells (with diameter of about 100-200 Mm) has also been suggested both by theory and observations [Simon and Weiss, 1968; Gilman, 1975; Wilson, 1987; Brajša et al., 1992; Miesch, 2005; Nordlund et al., 2009; Weber et al., 2013; Hathaway...
et al., 2013; McIntosh et al., 2014]. However, the physical origins of granulation and giant cells are poorly understood [Lord et al., 2014]. Another scale of convective cells, intermediate between granulation and supergranulation called mesogranulation were detected by November et al. [1981], and have a typical diameter of about 5-10 Mm and lifetime at least 2 hours. However, the existence of the mesogranulation scale seems controversial as there exist observational studies that have claimed that there is a lack of a distinctive mesogranulation scale [Rincon and Rieutord, 2018].
3. Solar wind

The heliosphere (the interplanetary space) is the near-Sun space which covers up to 120AU (1AU, astronomical unit, the distance between the Sun and Earth is about $1.5 \times 10^8$ km) from the Sun and is filled by the solar wind. The solar wind is a flow of plasma (ionized solar gas) outward from the sun to the interstellar space, which results from the difference in pressure between the solar corona and the surrounding space. Embedded in the plasma is the solar magnetic field called the heliospheric magnetic field (HMF), also called the interplanetary magnetic field (IMF) or the open solar magnetic field. The existence of solar wind was first suggested in the 1950s based on observations of comet tails [Biermann, 1951]. In the late 1950s the first solar wind theory was formulated [Parker, 1958]. Parker [1958] suggested a continuous supersonic (speed greater than speed of sound) and radial solar wind flow, which has the spiral structured HMF embedded within it.

Several space missions have been carried out to provide direct (in-situ) observations of solar wind already since the 1960s. Solar wind observations by Mariner 2 spacecraft [Neugebauer and Snyder, 1962] showed the continuous presence of solar wind and heliospheric magnetic field with similar properties as predicted by Parker [1958]. Space observations of solar wind have been mostly made from spacecraft in the ecliptic plane, i.e., they have been limited to the region within $\pm 7.2^\circ$ latitude of the solar equatorial plane (the range of the Earth’s annual location). However, there are some space missions which have deviated significantly from the ecliptic plane. Pioneer 11 was the first to be departed from the ecliptic plane [Smith et al., 1978] being now roughly at 17.3° heliographic latitude above the equator. Voyagers 1 and 2 departed from the ecliptic plane after planetary flyby and explored the mid-latitude heliosphere. Voyager 1 and 2 are now located roughly at 34.8° above and 32.5° below the equator respectively. The Ulysses spacecraft was the first mission to explore the heliosphere up to polar latitudes, passing from $-80^\circ$ to $+80^\circ$ heliographic latitude [Smith et al., 2000].
3.1. Solar wind properties

The most extensive and detailed observations of solar wind have been made from spacecraft near the orbit of the Earth or at 1 AU. The near-Earth solar wind measurements obtained from several spacecraft since the 1960s are archived in the NASA OMNI database. Solar wind consists mostly of protons and electrons, with a small fraction of He$^{++}$ ions (about 5%) and a smaller fraction of heavier ions (e.g., C, N, O, Ne, Mg, Si, S, and Fe). At 1 AU, the solar wind has proton density of $6.6 \text{ cm}^{-3}$, electron density of $7.1 \text{ cm}^{-3}$ and He$^{++}$ density of $0.25 \text{ cm}^{-3}$. The protons in the solar wind have a temperature of $1.2 \times 10^5 \text{ K}$, electrons temperature being $1.4 \times 10^5 \text{ K}$.

3.2. Types of solar wind

A typical solar wind speed at 1AU is about 450 km/s. With this speed it takes for the solar wind about 4 days to reach the Earth. However, the solar wind flow is not always the same. Solar wind speed depends on solar magnetic field structure. Richardson et al. [2000] classified solar wind flow into three types, the high-speed streams (speed greater than 450 km/s; originates from coronal holes), the slow solar wind (associated with the streamer belt or closed solar magnetic loops) and transient flows (related to coronal mass ejections).

Figure 3.1 shows the structure of solar wind as observed by Ulysses. Ulysses observations in its first orbit during solar minimum times in mid-1990s show a bimodal structure of solar wind, with persistently fast, tenuous and uniform solar wind at high heliolatitudes and slower, more variable, and highly structured wind at low latitudes [McComas et al., 1998]. In its second orbit near solar maximum around 2000 Ulysses observed a highly variable solar wind flow at all heliolatitudes [McComas et al., 2003].

3.3. Heliospheric magnetic field

The Interplanetary Monitoring Platform (IMP-1) satellite, which was launched in November 1963, was the first interplanetary space probe capable of revealing the existence of the heliospheric magnetic field (HMF) sector structure, i.e, the organization of the large-scale HMF into sectors of opposite polarities oriented predominantly away or toward the Sun [Wilcox and Ness, 1965]. Oppositely oriented sectors are separated by sector boundaries. The polarity of a sector remains the same for a time interval varying from couple of days to two weeks. During one solar rotation (about 27 days) typically two sector structures (switching polarity every 13-14 days), four sectors (switching polarity every 6-8 days), or sometimes another number of sectors are observed. In paper I we found that the two-sector
structure dominates at 1 AU, although the sector structure varies significantly with solar cycle, solar cycle phase, and hemisphere.

Wilcox and Ness [1965] demonstrated that the pattern of positive and negative polarity fields recurs at intervals of a solar rotation, indicating that the sector pattern is corotating with the Sun. They also showed that sector structure had a closely similar pattern in the photosphere, which gave evidence of the solar source of HMF sector structure. Later, the photospheric source of the HMF was confirmed by several studies [Svalgaard et al., 1975; Svalgaard and Wilcox, 1976]. In paper I, we confirm this early finding in a detailed comparison of the photospheric and heliospheric magnetic fields.

3.4. Heliospheric current sheet

The northern and southern solar magnetic hemispheres are separated by a magnetic neutral line, also called the solar magnetic equator. The solar magnetic equator is inclined at an angle $\alpha$ (the so-called tilt angle) with respect to the solar equatorial plane. The heliospheric current sheet (HCS) is the extension of neutral line into space. Accordingly, HMF sectors and sector boundaries can be interpreted in terms of the crossing of the heliospheric current sheet [Schulz, 1973]. An appropriate analogy of the HCS is a ballerina skirt, where the warps of the HCS are folds in the skirt. Note that the warps (flapping surface) of the HCS are created by the nonuniform distribution of the coronal holes and active regions on the solar surface. The structure of the heliospheric current sheet greatly varies over
the solar cycle, being very flat and aligned with the heliographic equator during solar minimum times, but more complicated and highly tilted with respect to the equator during solar maximum times.

The top panel of Figure 3.3 shows the maximum extent in latitude of the estimated heliospheric current sheet (HCS) in 1976-2019. The bottom panel gives the 13-month running mean sunspot number. The maximum latitudinal extent of the HCS was calculated using the potential field source surface (PFSS) model applied to photospheric magnetic field observations by Wilcox Solar Observatory (WSO). As can be seen from Figure 3.3, the HCS tilt angle varies systematically over sunspot cycle, being much larger during solar maximum times than minimum times. Tilt angles in the north and south do not show significant difference. Note also that the maximum tilt values are limited by the poor WSO resolution at high latitudes.

In order to observe the HMF sector and the associated HCS, the heliographic latitude of the observer must be less than the tilt angle of the HCS. For instance, an observer at 30° heliographic latitude will observe a unipolar HMF if tilt angle is less than 30°. The first example of the observation of only one sector during a few solar rotations was by Pioneer 11 when it was at +16° heliographic latitude in February 1976 [Smith et al., 1978]. The absence of the negative sector implied that the spacecraft was above the current sheet, and that the HCS tilt must have been less than 16°.

The dominance of the positive polarity observed by Pioneer 11 above the eclipt...
Fig. 3.3. Top panel shows the maximum tilt of the HCS according to WSO PFSS model for each rotation in 1976-2019. The mean values of the northern (blue) and southern (red) tilts are shown in black line. Bottom panel shows the 13-month running-mean sunspot number obtained from the SIDC.

tic in the 1970s confirmed the earlier studies that there exists a latitude-dependent dominant polarity [Rosenberg and Coleman, 1969]. This means that when moving to higher northern latitudes from the equator, the fraction of the HMF polarity, which have the same sign as the field of the northern pole increases with latitude. On the other hand, when moving to higher southern latitudes from the equator, the fraction of the HMF polarity, which have the same sign as the field of the southern pole increases with latitude.

However, a detailed comparison of the dominant polarities of the northern and southern heliographic hemispheres reveals a systematic pattern so that the occurrence fractions for the HMF polarity dominant in the northern heliographic hemisphere are found to be larger at 1 AU than the occurrence fractions of the dominant polarity in the southern hemisphere during the declining and minimum phases of the solar cycle [Mursula and Hiltula, 2003]. This implies that areas of the positive and negative polarities are different so that the dominant polarity of the northern hemisphere covers a larger area than the dominant polarity in the southern hemisphere [Smith et al., 2000; Mursula and Hiltula, 2003]. This also implies that the average heliospheric current sheet is slightly shifted or coned southward. The HCS may show momentary shifts either northward or southward. However, the southward shifted HCS is a persistent pattern during the declining to mini-
mum phase of all studied solar cycles, a phenomenon called the bashful ballerina
[Mursula and Hiltula, 2003]. Since the positive and negative magnetic fluxes must
balance (conservation of magnetic flux), the magnetic intensity of the field domi-
nant in the southern hemisphere must be stronger than the north. This has also
been verified both with photospheric [Zhao et al., 2005; Virtanen and Mursula,
2014; Virtanen and Mursula, 2016] and heliospheric observations [Virtanen and
Mursula, 2010; Erdős and Balogh, 2010].

In paper I we studied the evolution of sector structure and the corresponding
Hale boundaries. Hale boundary is the part of the sector boundary where the
change in polarity matches with the Hale polarity rule of sunspots in that hemi-
sphere.
4. Solar cycle

Sunspots are dark patches on the Sun, due to the emergence of magnetic flux at the solar surface. They appear dark (have temperature about 4000 K compared to 5800 K in the surrounding photosphere) as shown in Figure 4.1 due to the partial suppression of convection by a strong magnetic field. Sunspot scale size ranges between several thousand kilometers to several tens of thousands of kilometers. Some Sunspots appear unipolar, mostly in pairs (a bipolar magnetic field configuration), and others in more complex structure. Their lifetime may be up to 100 days. Sunspots have been observed and studied over several centuries. The most common feature of sunspots is the rise and fall of their number and area with the 11-year solar cycle [Schwabe, 1849]. A new solar cycle begins at a minimum in sunspot number and ends at the next minimum.

Our knowledge of the long-term evolution of solar magnetic field largely relies on sunspot counts. The past solar-activity over millennia has been studied using indirect proxies, such as the cosmogenic isotopes $^{14}$C and $^{10}$Be [Usoskin, 2017]. The international sunspot number series, a key indicator of solar activity, covers the time from the early-18th century onwards [Clette et al., 2014]. Solar magnetic activity experienced a dramatic increase from low activity around 1900 to the Grand Modern Maximum, peaking in the late 1950s, and experiencing a rapid decline after 2000 [Hathaway, 2015].

Figure 4.2 shows the monthly averages of the daily international sunspot number between 1749-2019, which cover 24 solar cycles. The data is obtained from Solar Influences Data Analysis Center (SIDC). As can be seen from Figure 4.2, the sunspot number shows 11-year quasi-cyclic variation. The shape of the sunspot cycle also changes from one cycle to another.
4.1. Sunspot butterfly diagram

Spörer and Maunder [1890] showed that sunspots emerge at high latitudes when the cycle begins and then tend to emerge at progressively lower latitudes as the cycle progresses (Spörer’s law). This is illustrated by the well-known sunspot butterfly diagram shown in Figure 4.3. Figure 4.3 gives additional information on solar magnetism that is not reflected in sunspot numbers shown in Figure 4.2. For instance, an extended solar cycle has been studied using sunspot butterfly diagram. An extended solar cycle is discussed in Section 6.5.

4.2. Hemispheric sunspot number

Sunspot activity is often asymmetric between the northern and the southern hemispheres. Such a hemispheric asymmetry has been found to have same systematic features over the course of the solar cycle. The unequal sunspot activity in the northern and southern hemispheres was already noted in the early works of Spörer and Maunder [1890] and Maunder [1904] and has been extensively studied since then [see, e.g., Newton and Milsom, 1955; Waldmeier, 1971; Carbonell et al., 1993; Oliver and Ballester, 1994; Vernova et al., 2002; Temmer et al., 2006; Norton and Gallagher, 2010; Chowdhury et al., 2013].

During most recent solar cycles, the northern hemisphere sunspot activity is more active than the southern hemisphere in the ascending phase of the solar cycle, while the south is more active than the north during roughly three years of
Another obvious feature of sunspot activity is a sudden decrease in activity during the maximum time of a cycle, which can be seen for many cycles in Figure 4.2. As a result, around solar maximum there are often two activity peaks [Temmer et al., 2006; Norton and Gallagher, 2010]. The gap between these two peaks is called the Gnevyshev gap, first detected by Gnevyshev [1963]. Using sunspot data, Temmer et al. [2006] and Norton and Gallagher [2010] showed that Gnevyshev gap is a property of both the northern and southern hemisphere, but whether they occur simultaneously in the two hemispheres or not, is still in question.
Fig. 4.3. Sunspot area as a function of latitude and time obtained from the Royal Greenwich Observatory since 1874. Top panel shows sunspot butterfly diagram as a function of latitude and time, and bottom panel shows the fraction of the solar disk covered by sunspots as a function of time between 1875 and 2015. The plot is reproduced from Hathaway [2015] which was last updated by D. Hathaway in 2016.

Fig. 4.4. Excesses of one hemisphere over the other based on 13-month smoothed hemispheric sunspot number ($S_n$) obtained from SIDC. Excess of the southern hemisphere is shaded red and excess of the north is shaded green.
5. Evolution of the large-scale photospheric magnetic field

The photospheric magnetic field includes both large-scale and small-scale magnetic structures. Active regions containing sunspots are the most common manifestations of large-scale magnetic structures. Also, observations have shown that the strongest fields are found in active regions containing sunspots [Okamoto and Sakurai, 2018]. Small-scale magnetic structures are short-lived and most common in quiet regions of the Sun. Figure 5.1 shows examples of two types of magnetic structures, active regions containing sunspots and the quiet-sun regions. In this chapter large-scale magnetic structures are discussed. Small-scale magnetic structures are discussed in the next chapter.

The global solar magnetic field was first observed by manually measuring the wavelength positions of spectral lines on photographic plates, until Babcock [Babcock, 1953] introduced the first photoelectric solar magnetograph. Measurements of the magnetic field of the whole photosphere, also called the full-disk solar magnetograms have been recorded on a daily basis, starting at the Mount Wilson Observatory (MWO) in the early 1950s.

After a series of measurements since 1952, Babcock and Babcock [1955] observed three outstanding solar magnetic features: Polar fields (original naming was "general fields"), bipolar magnetic regions (BMRs) and decaying active regions (original naming was "unipolar regions"). In this chapter we discuss briefly these main features of the photospheric magnetic field and their evolution.

5.1. Magnetic dynamo and the Hale cycle

The generation and evolution of magnetic fields in the solar interior and on the solar surface is thought to be caused by a dynamo mechanism operating in the solar interior. Large-scale solar dynamo involves the successively repeating gener-
Fig. 5.1. Example of positive (white) and negative (black) magnetic structure of a large sunspot (observed on 10 December, 2006) is shown in panel (a) and the magnetic structure of the quiet Sun (observed on 21 December, 2007) is shown in panel (b). The left image is saturated at \( \pm 1200 \) Mx per pixel, while the right has been saturated at \( \pm 50 \) Mx per pixel. Both images cover the same area \( (1.21 \times 10^{20} \text{ cm}^2) \) and have a pixel area of \( 1.17 \times 10^{14} \text{ cm}^2 \), and were observed with the Spectro-Polarimeter (SP) onboard Hinode/SOT. Image taken from [Parnell et al., 2009].

Formation of the poloidal field and the toroidal field from each other in a cyclic manner. Poloidal field lines are mainly oriented along the meridional plane as illustrated in panel (a) of Figure 5.2, and toroidal field lines are circles around the rotating axis as in panel (b) of Figure 5.2. The generation of toroidal field from poloidal field is called the omega (\( \Omega \)) effect and the generation of the poloidal field from toroidal field is called the alpha (\( \alpha \)) effect.

The current standard dynamo theory is the Babcock-Leighton model, also called solar flux-transport dynamo model [Babcock, 1961; Leighton, 1969]. A sequence of schematic diagrams that demonstrate the flux-transport model is given in Figure 5.2 with an initial stage of poloidal field lines shown in panel (a). The differential rotation of the Sun (the Sun rotates faster at the equator than at the pole) drags poloidal field lines around with it and creates a toroidal field in the solar interior as shown in panel (b) of Figure 5.2. Concentrated toroidal flux ropes tend to rise up to the surface by magnetic buoyancy, as indicated in panel (c). When the flux rope rises and breaks through the solar surface it can create bipolar magnetic regions, as shown in panels (d-f).

Bipolar magnetic regions decay and spread in latitude and longitude after their emergence, as shown in Figure 5.2 (f). Meridional flow (yellow circulation with arrows) carries surface magnetic flux (mostly the trailing-polarity flux) poleward,
Fig. 5.2. Schematic diagram of solar flux-transport dynamo processes. Red inner sphere represents the Sun’s radiative core and blue mesh the solar surface. In between is solar convection zone where dynamo resides. Shearing of poloidal field by the Sun’s differential rotation (a) produces toroidal field (b). When toroidal field is strong enough, buoyant loops rise to the surface and forms BMRs from these loops (c). Additional flux emerges (d and e) and spreads (f) in latitude and longitude from decaying spots. Meridional flow (yellow circulation with arrows) carries surface magnetic flux poleward, causing polar fields to reverse (g). Some of this flux is then transported downward to the bottom and towards the equator (h). This reversed poloidal flux is then sheared again near the bottom by the differential rotation to produce the new toroidal field (i), opposite in sign to that shown in (b). Image taken from [Dikpati and Gilman, 2007].
causing polar fields to reverse as shown in Figure 5.2 (h). Some of this flux is then transported downward to the bottom of the convection layer and towards the equator and forms the new poloidal fields (i) of reversed polarity compared to (a). Then this reversed poloidal flux is sheared again by the differential rotation to produce the new toroidal field opposite in sign to that shown in (b). This cyclic process has a period of 22-years. The leading-polarity flux regions in each hemisphere come into contact with each other and reconnect to form trans-equatorial loops.

5.2. Properties of bipolar magnetic regions

As already briefly described above, magnetic flux emerges at low to mid-latitudes of the solar surface, producing tilted bipolar magnetic regions (BMRs). The tilt angle of bipolar magnetic regions is defined as the angle between a line connecting the leading and trailing polarities of the BMRs and the east-west (E-W) line along a constant latitude as illustrated in Figure 5.3. The tilt angles of ARs normally follow Joy’s law [Hagenaar et al., 2003; Hagenaar et al., 2008; Tlatov et al., 2010; van Driel-Gesztelyi and Green, 2015] according to which, the axis is tilted with respect to the east-west direction as illustrated in Figure 5.3, the leading polarity of the ARs being at a slightly lower latitude than the trailing one [Hale et al., 1919].

BMRs range from strong, large active regions often containing sunspots to small, ephemeral bipoles that populate the quiet Sun [Hagenaar et al., 2003; Hagenaar et al., 2008; Tlatov et al., 2010; van Driel-Gesztelyi and Green, 2015]. In this section we will discuss large active-region BMRs. Ephemeral bipoles will be discussed in the next chapter.

The magnetic flux and area of ARs are closely correlated over a broad range of scales from small regions (pores) to large regions, as shown in Figure 5.4. As can be seen from Figure 5.4, small sunspots have magnetic fluxes of about $10^{20}$-$10^{21}$Mx and large active regions have magnetic fluxes of about $10^{21}$-$10^{22}$Mx. The lifetimes of small active regions may be days, whereas large active regions may last for weeks or months depending on the phase of solar cycle [Hagenaar et al., 2003; Hagenaar et al., 2008; Tlatov et al., 2010; van Driel-Gesztelyi and Green, 2015]. The latitude zones where BMRs emerge, migrate toward the equator as the solar cycle progresses, which leads to the butterfly diagram [Hale and Nicholson, 1925], similar to sunspots [Spörer and Maunder, 1890].

In general, there are well known asymmetries in BMRs [see, e.g., van Driel-Gesztelyi and Petrovay, 1990]. For instance, the flux of the leading polarity of BMRs tends to be more concentrated, e.g., in large well-formed sunspots, whereas the flux of the trailing polarity tends to be more dispersed and to have a fragmented
appearance. The magnetic neutral lines separating the fluxes of the two opposite polarities (also called inversion lines) in bipolar active regions are statistically nearer to the main trailing polarity spot than to the main leading spot [van Driel-Gesztelyi and Petrovay, 1990; Petrovay et al., 1990].

5.3. Decaying active regions

Decaying active regions favor one of the two polarities and, therefore, are partial unipolar regions. They originate from the evolution (diffusion, transport etc) of active regions (like BMRs), and can be transported from the mid-latitude source region either to lower latitudes (mainly the leading part) or to higher latitudes (mainly the trailing part). The trailing polarity parts of the decaying active regions are transported to the poles in terms of so-called polar surges, where they cancel the old polar field and create the new polar field of opposite polarity [Babcock, 1961; Leighton, 1969].

Figure 5.5 shows this transport of surges of new flux to the poles and the eventual reversal of the polar field quite clearly. (In fact, this poleward transport dominates the visual image of the butterfly diagram of the photospheric field, making the butterfly fly to the right, i.e., to a direction opposite to that of the sunspot butterfly).
Recent studies have shown the occasional occurrence of poleward surges of leading (old) polarity flux, but they are more seldom than normal trailing (new) polarity surges. The existence of old-polarity surges (also called counter-surges) implies that the leading polarity field can also affect mid- and high-latitudes. Figure 5.5 shows both normal and counter surges. Counter-surges may occur, e.g., if the axis of the BMR is tilted opposite to Joy’s law [Ulrich and Tran, 2013]. It has been shown that the orientation of BMRs is scattered, not perfectly uniform [see, e.g., Stenflo and Kosovichev, 2012]. However, despite such scatter, the poleward surges are always dominated by trailing polarity surges at high latitudes as shown in Figure 5.5.
Fig. 5.5. Top panel: Magnetic field butterfly diagram also called supersynoptic map constructed by combining the longitudinally averaged radial magnetic field obtained from the MWO instrument in 1974–2010 and by the HMI instrument onboard SDO satellite in 2010–2019. Red color indicates positive (outward) polarity and blue negative (inward) polarity. Units are in Gauss. For reference, monthly sunspot number obtained from the SIDC is shown at the bottom panel.

5.4. Photospheric Hale boundary

The large-scale unipolar magnetic regions are separated by magnetic neutral lines in the photosphere, also called sector boundaries. Photospheric sector boundaries are extended to the corona and to the heliosphere and form the heliospheric current sheet. The neutral lines of active regions may first be separate from the neutral lines of the large-scale solar structure [Svalgaard and Wilcox, 1976]. Figure 5.6 shows the magnetic neutral line of the WSO synoptic map for CR 2210, i.e., the time between 26 October–23 November, 2018 (upper panel) and the baseball seam can be considered as analogous to the neutral line (bottom left panel). The two bottom panels of Figure 5.6 show the schematic view of the magnetic neutral lines for odd and even solar cycles, respectively.

The part of the photospheric sector boundary where the polarity change of fields agrees with the Hale polarity law in that solar cycle and hemisphere is called Hale
Fig. 5.6. Upper panel shows the WSO synoptic map for CR 2210, i.e., for the time between 26 October – 23 November, 2018. The solar magnetic neutral line is shown in green curve, and the horizontal black dashed line denote the solar heliographic equator. Bottom left panel shows the baseball seam structure analogous to the oversimplified neutral line shape that has a four-sector solar field structure, the plus and minus sign indicating the positive and negative sectors, respectively. Bottom third and fourth panels show schematic view of the photospheric Hale boundary (thick purple lines) for odd (left panel) and even (right panel) cycles during periods when four-sector boundary crossings would be detected at the Earth. Positive magnetic polarity is indicated by yellow, negative by blue. The third and fourth panels images are obtained from Loumou et al. [2018]

sector boundary [Svalgaard and Wilcox, 1976] as shown as thick purple lines in the two bottom panels of Figure 5.6. The middle bottom panel of Figure 5.6 shows the Hale boundary (+,– Hale boundary in the north and –,+ Hale boundary in the south) for the declining phase of an odd solar cycle, while the bottom right panel shows for an even solar cycle (–,+ Hale boundary in the north and +,– Hale boundary in the south). Studies have shown that the photospheric magnetic field is concentrated near the Hale boundary. It has also been shown that solar flares appear preferentially at Hale boundaries. In paper I, we showed that the position of Hale boundary varies over the course of solar cycle, so that its latitudinal position migrates towards the equator as the solar cycle progresses. The photospheric Hale boundary is detectable even in the heliospheric magnetic field at the Earth, as we showed in paper I.
5.5. Polar region fields

The solar polar magnetic fields are manifestations of the solar poloidal fields that serve as the seed field for the solar dynamo that generates the toroidal fields of the next cycle, from which the active regions are created. Polar fields are located around the heliographic poles of the Sun, usually above the absolute heliographic latitude of $55^\circ$.

Figure 5.7 shows an example of magnetic landscape of the polar region of the Sun obtained on 16 March, 2007 by the Hinode Solar Optical Telescope (SOT) Spectro-polarimeter (SP) from above the south pole. As can be seen from Figure 5.7, polar fields are concentrated to small regions of strong field which can be in the orders of kG.

Polar fields are important parameters for the overall solar activity and for the heliospheric magnetic field. Polar coronal holes are the source of fast solar wind, which is freely channeled along unipolar magnetic fields [see, e.g., Krieger et al., 1973].

Figure 5.8 shows an example of the signed strength of the polar fields around north pole in the late declining phase of solar cycle 23. Polar regions have mixed polarity fields, i.e., both positive and negative polarities exist as shown in Figure 5.8. However, they are already predominantly unipolar with opposite polarity at the two heliographic poles. As shown in the upper panel of Figure 5.8 a dominant negative-polarity is seen. Figure 5.8 shows that the large magnetic concentrations in the polar region have mainly the same magnetic polarity, while the smaller patches have mixed polarities. As can be seen in Figure 5.8, the magnetic landscape of the polar region is characterized by vertical kilogauss patches and ubiquitous weak horizontal magnetic fields.

Babcock [1959] showed that the polar field reversed its polarity around solar maxima, out of phase with the polarity reversal of the sunspot cycle, and that the reversal time was not always the same in the two hemispheres. Since then, several studies have studied the timing of the solar polar field reversal in the two hemispheres [e.g., Makarov et al., 1983; Durrant and Wilson, 2003; Benevolenskaya, 2007; Virtanen and Mursula, 2010; Svalgaard and Kamide, 2013; Sun et al., 2015; Petrie, 2015; Virtanen and Mursula, 2016; Gopalswamy et al., 2016]. In most recent cycles, the polar field reversal has first occurred in the northern hemisphere, and somewhat later in the southern hemisphere as can also be seen in Figure 5.9.
5.6. Unipolar fields opening up to the heliosphere

The photospheric magnetic field is also the source of the heliospheric magnetic field. Decades of observations of the photospheric magnetic field and the related modeling of the coronal field have shown that magnetic fields from the unipolar regions extend out into the heliosphere and form the heliospheric magnetic field.

The identification of the solar source of HMF sector structure began in the early 1970s. Gulbrandsen [1973] and Antonucci and Svalgaard [1974] first found a signature of the HMF structure in the solar corona. A good agreement was obtained between the sector boundaries in HMF and corona. Later, it became evident that HMF sector structure observed at 1AU has largely the same pattern also in the photosphere and that there is a strong connection with the Hale boundaries [Svalgaard et al., 1975; Svalgaard and Wilcox, 1976]. Our results confirm these earlier findings. In paper I, we studied Hale boundaries separately in the northern and
Fig. 5.8. An example of a map of signed strength of the vertical (a) and horizontal (b) magnetic field around north pole taken on 25 September, 2007 by Hinode/SOT. Figure is taken from Ito et al. [2010].

southern hemispheres in the four different phases of solar cycles 21-24. We also estimated the statistical significance of Hale boundaries.
Fig. 5.9. Evolution of the polar field in the two hemispheres (between about absolute latitudes of 55° and the poles) as measured at WSO in 1976-2019. The north, south and the mean values are shown in blue, red and black lines.
6. Evolution of the quiet-Sun photospheric magnetic field

Soon after his discovery of magnetic fields in sunspots [Hale, 1908], George Ellery Hale tried and led a foundation to explore the magnetic property of the non-spot regions of the Sun [Stenflo, 2017]. Alas, due to the limitations of instruments, for a long time, the magnetic features of quiet Sun were not studied in detail, if not ignored completely. Nowadays, due to an increasing spatial and spectral resolution of magnetic field measurements, the magnetism of the quiet Sun (QS) and the associated smallest magnetic features resolvable with current instruments have become a topic of active research. The quiet Sun is the area of the solar surface outside of sunspots and active regions. The quiet-Sun magnetism consists of granular, internetwork (IN), network (NE) and ephemeral region (ER) fields [Bellot Rubio and Orozco Suárez, 2019].

Figure 6.1 shows an example of a full-disk image taken by SDO/HMI on 4 April, 2012. The SDO/HMI instrument with a high spatial resolution of about one arc-second gives 4096×4096 pixels full-disk images that reveal that the Sun’s surface is permeated with positive and negative magnetic features covering a wide range of sizes from the smallest flux elements observed at the resolution of the SDO/HMI instrument to large active regions containing sunspots. Figure 6.1 shows the photospheric magnetic field covering different ranges of scales including network, ephemeral regions, active regions, decaying active regions and polar fields. Recently, using SUNRISE/IMaX instrument which has a spatial resolution of 0.15–0.18 arc-second [Solanki et al., 2011] and Hinode/SOT instrument which has a spatial resolution of 0.2–0.3 arc-second [Suematsu et al., 2008], the magnetic structure of the quiet Sun down to the granulation scale has been revealed. It is still an open question whether the quiet Sun’s magnetic field is created only by the global dynamo (discussed in Section 5.1) or by a small-scale dynamo driven by near-surface convective flows [Petrovay and Szakaly, 1993] in addition to the global dynamo.
Fig. 6.1. A SDO/HMI full-disk image of the photospheric magnetic field taken on 4 April, 2012, with positive and negative fields shown as bright and dark, respectively, and indicates (1) polar field, (2) a large-scale unipolar field, (3) an active region, (4) an ephemeral region and normal network, (5) a decaying active region and (6) enhanced network field. The two sunspot bands north and south of the equator can clearly be seen. Image obtained from Priest [2014]

6.1. Granular magnetic fields

The smallest so far resolvable magnetic features are the magnetic elements at the granulation scale (granulation scale is discussed in Section 2.3). The weakest fluxes measured in granular features at the resolution of current instruments has a magnetic flux of about $10^{15} - 10^{16}$ Mx [Zirin, 1987; Lites et al., 1996; Lin and Rimmele, 1999]. Granular fields have short life-times that may last only for minutes. The orientation and organization of granular magnetic fields have been under debate. Some report that granular fields appear as transient horizontal fields [Ishikawa et al., 2008], and a significant fraction of them appear as magnetic loops [Martínez González and Bellot Rubio, 2009], while others report the observation of vertical and unipolar fields in granular cells [Orozco Suárez et al., 2008].

Figure 6.2 shows examples of SUNRISE/IMaX instrument magnetograms at six different spatial resolutions. The top left panel shows the original highest resolution magnetogram, while the others show the same magnetogram reduced to a low resolution. The original magnetogram shown in Figure 6.2 has a resolution of 0.14", which reveals solar magnetic structures down to the granular scale. Figure 6.2 also shows the effect of spatial resolution on the structure of magnetic features. As the spatial resolution of the magnetogram is decreased, the number of features that remain visible decreases. As shown in the bottom left panel of Figure 6.2, at about 0.88" resolution, magnetic elements about 1" in diameter are still clearly distinguishable. But at a very coarse spatial resolution of 3" as shown in the bot-
Fig. 6.2. SUNRISE/IMaX magnetogram at six different spatial resolutions. The top left panel shows the magnetogram at the original resolution. The other panels show the magnetograms corresponding to different resolutions indicated in the titles. Image taken from Bellot Rubio and Orozco Suárez [2019].

tom right panel, the granular structure is no more visible and the magnetogram looks rather blurred. Note that the granular field structures are not visible in the current full-disk magnetograms. For instance, the 3′ Wilcox Solar Observatory (WSO) and 12″ or 20″ Mount Wilson Observatory (MWO) instruments, which performed the longest series of measurements in the history of solar physics, have too coarse a resolution for the granular fields to be visible. Even fields at super-granular scales are barely visible at MWO and invisible at WSO.
6.2. Internetwork fields

Another group of magnetic field features discovered by Livingston and Harvey [1975], with magnetic field of the order of 100 G (weaker than network), are internetwork regions. They represent fields in the interior of supergranular cells (supergranulation scale is discussed in Section 2.3). Individual internetwork elements live only for minutes to hours [Wiegelmann et al., 2014; Borrero et al., 2017; Bellot Rubio and Orozco Suárez, 2019]. Internetwork fields have predominantly a horizontal structure [Lites et al., 2017]. The individual IN elements have magnetic fluxes of roughly $10^{16} - 10^{18}$ Mx, the lower limit only reflecting the current resolution of instruments. The right panel of Figure 6.3 shows an example of quiet-Sun magnetic map using an upper limit for the magnetic flux of 25 G. The map shown in the right panel of Figure 6.3, reveals IN field elements filling the interior of supergranular cells.

6.3. Network fields

The photospheric magnetic network often outlines the borders of supergranular cells, where the horizontal flows turn into downflows [Sheeley, 1967; Bellot Rubio and Orozco Suárez, 2019]. The left panel of Figure 6.3 shows an example of Hinode/SOT magnetogram using an upper limit of 500 G, which reveals NE fields,
white arrows showing one example of such a field structure. Network patches are persistent and can have life-times of hours and even days. The NE observed on the solar surface is permeated by magnetic fields of the order of kilogauss (kG). The networks are of mixed polarity features. Individual network elements have magnetic fluxes of roughly $10^{18} - 10^{19}$ Mx [Hagenaar et al., 2003]. Although the magnetic network structure is known already since the 1960s, their origin and detailed structure remain still an open question.

6.4. Ephemeral Regions

Ephemeral regions are small bipolar magnetic regions without sunspots that are seen typically for only 1–2 days after their emergence. They have smaller area (typical diameter of about 10-15 Mm) than sunspot-containing active regions. ERs have magnetic fluxes of roughly $10^{18} - 10^{20}$ Mx. The term ephemeral for short-lived bipolar regions was apparently first used by Dodson [1953]. However, the significance and systematic presence of ERs in very large numbers was discovered by Harvey and Martin [1973].

ERs are widely distributed over the solar surface (their latitudinal distribution is broader than that of larger active regions), but more common in the active region belts [Harvey, 1993]. Hagenaar et al. [2003] argued that the broad latitude distribution of the newly emerged ERs does not show a clear butterfly pattern exhibited by active regions. Ephemeral regions have been observed to emerge in the high-latitudes earlier than sunspots.

The occurrence of ERs over a solar cycle is less understood. It has been argued that the number of ERs vary in anti-phase with the solar cycle [Martin and Harvey, 1979; Hagenaar et al., 2003], with only a weak correlation between ERs and larger active regions. A weak connection in activity between small and large bipolar regions implies that the activity of small bipolar regions may lead the extension of solar activity cycle, beyond the usual sunspot activity cycle [Petrie et al., 2014]. Although ERs have been studied in detail since their discovery, their generation, characteristics and relation with larger active regions include still many open questions [van Driel-Gesztelyi and Green, 2015].

6.5. Extended solar cycle

The equatorward migration of the location of emergence of sunspots, which forms the sunspot wing (also called the activity band) and the poleward surges (also called the rush-to-the-pole) of dispersed magnetic flux are the two most common
features on the solar surface. The first of these migrations is an essential part of the 11-year solar cycle (Schwabe cycle) and the second of the 22-year magnetic cycle (Hale cycle).

The extended solar cycle describes the presence of magnetic activity during a time longer than the time between two sunspot minima, with successive cycles coexisting for a certain time. The butterfly diagram (see Figure 4.3) gives a good example of an extended solar cycle that shows the overlap of wings for a certain time. As mentioned earlier in Chapter 4, the sunspot number has a period of around 11 years. However, the butterfly diagram indicates that the wings overlap so that sunspots corresponding to each cycle are present for about 13–14 years. Small-scale bipolar regions (like ERs) have been shown to emerge about 5 years earlier than sunspots, so the ER activity related to one cycle extends to about 17–18 years [Wilson et al., 1988; Harvey, 1992]. Sunspot activity is simply the main phase of a more extended cycle (wing).

The extended solar cycle has also been studied using observations of the torsional oscillations, the alternation of faster and slower (than average) latitude zones [Howard and Labonte, 1980]. Torsional oscillations are observed both on the surface and in the convection zone. The pattern migrates towards the equator in the mid-latitude region below 60° and towards the poles in the high-latitude region above 60° [Antia and Basu, 2001; Ulrich, 2001].

The extended solar cycle has been also studied using solar magnetic field observations [Shrauner and Scherrer, 1994; Lo et al., 2010; Ulrich and Boyden, 2005]. For instance, Shrauner and Scherrer [1994] using WSO data and Ulrich and Boyden [2005] using MWO data showed that a new toroidal cycle begins at high latitudes (near 60° latitude), soon after the maximum of a sunspot cycle, providing evidence for an extended cycle. Note that the toroidal cycle is studied using toroidal (also called zonal or azimuthal) field calculated from the line-of-sight magnetic field [Shrauner and Scherrer, 1994; Lo et al., 2010; Ulrich and Boyden, 2005] or from vector magnetic field observations [Virtanen et al., 2019].

Currently, using the longest and continuous WSO full disk magnetograms, it has become possible to study the nature of the extended solar cycle for almost 44 years, i.e., during two full magnetic cycles or four sunspot cycles. Figure 6.4 shows the sign of toroidal fields obtained from the WSO that covers a small part of cycle 20, full wings of cycle 21–23, almost full wings of cycle 24 and the start of the wings of cycle 25. The direction of the toroidal field is calculated using the approach by Shrauner and Scherrer [1994] where they calculated the east-west inclination angle between a field line and its local radial vector. Note that a positive inclination angle (blue) is in the direction of solar rotation (westward) and negative (red) in the direction opposite to solar rotation (eastward). As can be seen in Figure 6.4, the new wings of the extended solar cycle begins after the maximum of current sunspot cycle (n cycle). When the solar minimum of n cycle reaches, the next extended cycle (n + 1) will be about 4–5 years old. As a result
Fig. 6.4. Upper panel: Monthly sunspot number obtained from the SIDC. Bottom: Representation of an extended solar cycle based on the direction of the toroidal component of magnetic fields obtained from WSO observations in 1976–2019. The arrows and colors indicate the direction of the inferred east-west field, red and blue colors showing negative (eastward) and positive (westward) fields, respectively. The intensity of the color indicates the magnitude of the inclination angle (measure of the east-west deviation of the field line from vertical). Vertical red and black lines indicate solar maximum and minimum times, respectively. The horizontal blue lines are at 15° absolute latitude. Span of each toroidal cycle (wing separators) are shown by the blue line. Image courtesy Phil Scherrer.

the 11–13 year solar cycle is extended to approximately 17–18 year wing.
7. Asymmetry of the photospheric magnetic flux

Photospheric magnetic field measurements are used to derive the field strength, magnetic flux density and magnetic flux. Magnetic field strength is the observed field strength of magnetized plasma and the magnetic flux density is the mean field strength within the pixel. It is often assumed that inside the pixel there are plasma elements that are either non-magnetized or uniformly magnetized. The fractional area of magnetized plasma is called the filling factor, and the flux density is derived by multiplying field strength by filling factor. However, derivation of filling factor requires very detailed information on spectral line profiles. That is why synoptic full-disk data sets usually rely on the assumption that filling factor is unity and the field strength is equal to flux density.

More realistically, the magnetized plasma may contain both stronger or weaker fields, even of opposite orientation (polarity) [Stenflo, 2010]. Fields of opposite polarity cancel each other in the derivation of magnetic field from polarized light. Accordingly, the current data-sets give flux densities, not the ultimate field strengths of the smallest magnetic elements that we could obtain in the case of a fully resolved magnetic structure. In the limit of infinite resolution, the difference between flux density and field strength would disappear [Stenflo, 2010]. Therefore, the term magnetic field intensity or magnetic field value (that we mostly use in this thesis and in Papers I–IV) refers to the magnetic flux density, i.e., the mean vectorial field value over the respective spatial resolution pixel.

As discussed earlier, the distribution of the magnetic flux on the solar surface is complex. Consequently, selecting the distribution function to fit the distributions of observed fluxes is a point of discussion. Parnell et al. [2009] studied the flux distribution of all currently observable surface magnetic features covering six orders of magnitude in flux ($10^{17} - 10^{23}$ Mx) and 10 orders of magnitude in frequency (emergence rate). They found that the distribution of all flux features, regardless of field strength, follow the same power law distribution, as shown in Figure 7.1. It can be also seen in Figure 7.1 that the smaller the scale, the higher the emergence rate of flux. Note that the power law gives the highest total fluxes to the smallest elements. Zirin [1987] found that the rate of magnetic flux in IN fields is about...
Fig. 7.1. (a) Histograms of fluxes of magnetic features observed in the Hinode/SOT data in June, 2007 (blue), MDI high-resolution data in October, 2005 (green), and MDI full-disk data in May, 1998 (red). (b) As (a), except here the SOT data (blue) compared with December, 2001 (orange) and December, 2007 (cyan) MDI full-disk data. The dashed line in both graphs is a fit to the data in (a) and has the slope of 1.85 [Parnell et al., 2009].

10^2 and 10^4 times larger than in ERs and ARs, respectively. Similarly, each AR typically carries 100 times as much flux as an ER. However, the rate of emergence of ERs is about 10^4 times larger than in AR regions. Consequently, ERs bring roughly 100 times more magnetic flux to the solar surface than ARs [Zirin, 1987].

A single power law distribution implies that the processes determining the spatial structure of surface magnetic features are independent of scale [Parnell et al., 2009]. Parnell et al. [2009] argued that magnetic features are produced by a solar dynamo that acts in the same way at all scales or, alternatively, that they have different origins, but that after their emergence into the solar atmosphere, all magnetic features are dominated by surface processes. Thornton and Parnell [2011] extended the earlier work by Parnell et al. [2009] to include the weak field end of the distribution, then spanning nearly seven orders of magnitude in flux (10^{16} – 10^{23} Mx) and 18 orders of magnitude in occurrence frequency. They confirmed that all magnetic elements appearing on the solar surface follow a single power law, verifying that all the magnetic features are created by the same mechanism. Stenflo and Kosovichev [2012] also speculated the same solar dynamo in generating both small- and large-scale fluxes.

A single power law of flux features over all observable scales was already discussed in earlier studies. Already in the 1970s, Harvey et al. [1975] suggested that bipolar magnetic regions occur at different scales, from the largest sunspot-
containing regions to the detected small-scale magnetic field elements, with a size spectrum that follows a power law and that ERs are the small-scale end of a broad spectrum of active regions [Harvey, 1993; Harvey and Zwaan, 1993; Schrijver and Harvey, 1994].

Recently, the single power law of magnetic flux is questioned. Muñoz-Jaramillo et al. [2015] studied the best-fitting distribution functions for 11 different databases of sunspot areas, sunspot group areas, sunspot umbral areas, and magnetic flux. They fitted log-normal, power law, exponential, and Weibull distribution functions and argued that flux distributions are bimodal, and are best fitted with a linear combination of Weibull and log-normal distributions. They argued that the flux distribution for small-scale structures (with fluxes below $10^{21}$ Mx) is a Weibull distribution and for the largest structures (with fluxes above $10^{22}$ Mx) is a log-normal distribution. This implies that a transition between the Weibull and log-normal components of the bimodal distribution occurs around $10^{21} – 10^{22}$ Mx. Although Weibull is a better fit, Muñoz-Jaramillo et al. [2015] reported that Weibull fit to small scale fluxes covering ($10^{16} – 10^{21}$ Mx), shows the expected linear behavior of a power-law fit of Parnell et al. [2009].

According to Muñoz-Jaramillo et al. [2015], the implication of the bimodal distribution of fluxes is the existence of two separate mechanisms (large-scale and small-scale dynamos) in the generation of field structures on the photosphere. The first is connected to the generation of large active regions, and the latter with the small-scale structures [Muñoz-Jaramillo et al., 2015]. A bimodal distribution of fluxes was also obtained by Tlatov and Pevtsov [2014].

### 7.1. Distribution of the signed photospheric magnetic field values

The existence of asymmetry in the magnetic polarity of the large-scale fields between the two solar hemispheres is well established. It has been studied using different solar proxies such as the magnetic flux density (see Section 3.4), sunspot activities (see Section 4.2), and the timing of polar field reversal (see Section 5.5). The existence of polarity imbalance between the positive and negative fields implies that the distribution of the signed field is not always locally symmetric. As discussed earlier, the magnetic field distribution in active regions is locally unbalanced systematically.

As discussed above, the measured photospheric magnetic field consists mainly of rather weak fields, despite the fact that a small number of active regions with very strong field values carry a considerable amount of the total magnetic flux. While the asymmetric distribution of the strong fields of active regions is a systematic pattern that has been studied in detail for a long time, the possibly asymmetric
7.2. Distribution of the signed weak-field values

Due to improved observational and diagnostic capabilities, there is increasing interest to study the weak photospheric magnetic field values. The weakest photospheric magnetic fields can be defined to have a field strength of about 10 G or less [Aschwanden, 2019]. Figure 7.2 shows an example (CR 2118) of HMI synoptic map at 3600×1440 resolution and the corresponding histogram distribution for field values between -50 G and 50 G with a bin size of 0.1 G. Figure 7.2 shows that the histogram distribution for the signed field values increases as the absolute field value decreases. The maximum of the distribution is close to but slightly shifted from zero, indicating that the distribution of signed fields may not always be symmetric.

7.2.1. Asymmetric distribution of signed weak fields values

The distribution of the weakest photospheric magnetic fields has not been studied in detail. Alas, due to difficulty in detecting the signal from noise, the weakest
photospheric magnetic field values have mostly been ignored by previous studies. However, there is some prior evidence for the asymmetric distribution of weak fields \cite{Ulrich2002, Berger2002, Liu2004}, but different authors have given different interpretations to this asymmetric pattern. This implies that the question of whether this asymmetric pattern is systematic and related to a physical feature of the weak fields \cite{Liu2004} or that it is a random pattern related to, e.g., to the artefact of measurement noise \cite{Ulrich2002} has not so far been resolved. In Papers II–IV we have studied the distribution of signed weak photospheric magnetic field values in detail. We fitted the histogram distribution of measured field values for each synoptic map (for several data-sets separately) with a parametrized Gaussian function to calculate the position of the peak of the Gaussian distribution. The Gaussian function of the following form:

$$\phi = c \exp \left( -\frac{1}{2} \left( \frac{B_i - a}{b} \right)^2 \right)$$  \hspace{1cm} (7.1)$$

is fitted to the observed histogram distribution. Here $B_i$ are the observed (weak) field values, and the three parameters $a$, $b$ and $c$ give the position of the peak (the shift or weak-field asymmetry), the width (standard deviation) and the height of the distribution, respectively. We calculated the rotational shifts of the maximum of the fitted Gaussian distribution of weak-field values and studied their statistical significance, temporal occurrence and similarity among the many data sets.

Figure 7.3 shows examples of both the histogram (top panels) and fitted Gaussian (bottom panels) distributions of weak photospheric magnetic field values (within ±10 G and with a bin size of 0.1 G) of HMI synoptic maps at five different resolutions for CRs 2118 and 2147. The main purpose of fitting a Gaussian function to the histogram distribution of the weak-field values is to quantify the degree to which the distributions are shifted toward positive or negative values. As can be seen in Figure 7.3, while the exact values of the histogram peaks are mainly random, the peak of Gaussian fits demonstrates a clear shift from zero (positive for CR 2118 and negative for CR 2147), which increases with reducing spatial resolution.

Our results in Papers II–IV give strong evidence for the systematic nature of a momentarily asymmetric distribution of weak fields. For the first time, we verified the physical nature of the weakest photospheric magnetic field values using completely independent magnetograph instruments and data sets for the same synoptic maps. This gives a clear evidence that the weak magnetic fields of synoptic data are much less noisy than it was thought to be and that the weakest magnetic fields are important signals in solar magnetism. It is worth noting that random noise does not introduce a systematic shift of the distribution of weak field values.
Fig. 7.3. Distribution of field values of HMI synoptic maps for CRs 2118 and 2147 at five different resolutions. Left and right upper panels show the histogram distribution for CRs 2118 and 2147, respectively. Bottom panels show the fitted Gaussian function for the upper panels.

### 7.2.2. Weak field shift and spatial scale

In order to investigate the effect of data resolution on the hemispheric weak-field asymmetries, we derived four additional sets of medium- and low-resolution HMI synoptic maps (360×180, 180×72, 120×48, and 72×30) from the 3600×1440 synoptic maps using simple block averaging method. The values of each pixel of the 360×180, 180×72, 120×48, and 72×30 resolution synoptic maps are block-averages of the values of 10×8, 20×20, 30×30 and 50×48 pixels of the original synoptic map, respectively.

Figure 7.3 lower left panel shows that the maxima of the Gaussian distributions of 3600×1440, 360×180, 180×72, 120×48, and 72×30 resolution HMI synoptic maps of CR 2118 are located at 0.02 G, 0.05 G, 0.17 G, 0.21 G and 0.22 G. Similarly, Figure 7.3 lower right panel shows that the corresponding maxima of the Gaussian distributions for CR 2147 are located at -0.02 G, -0.04 G, -0.07 G, -0.11 G and -0.15 G, respectively. This implies that the weak field shifts have the same
orientation for the different spatial resolution of the same magnetograph. In Paper II we studied the effect of spatial scale on the shift of the distribution for several data-sets, and showed that the weak field asymmetry of high- and low-resolution data have mainly (statistically significant) the same orientation indicating that the sign of the shift of a distribution is independent of spatial scale. We also showed in Paper II that the weak-field asymmetries increase with decreasing map resolution and that the fraction of significant weak-field asymmetries increases with decreasing resolution.

### 7.2.3. Weak field shift of several data-sets

Figure 7.4 shows the weak field asymmetry calculated from six independent magnetographs (most of which have overlapping observations). The weak field values are derived from the synoptic maps of photospheric magnetic fields observed at Wilcox Solar Observatory, Mount Wilson Observatory, Kitt Peak, SOHO/MDI, SOLIS/VSM, and SDO/HMI. As can be seen from Figure 7.4, the weak-field shift values of the different data-sets show a good agreement. This is outstanding, taking into account the many differences between the data sets due, e.g., to instrumental, measurement, and calibration differences, as well as the differences in the construction of synoptic maps. In Paper II, using these different data sets obtained since 1970s, we show that the distribution of weak fields is indeed shifted by a statistically significant amount. We also showed that the weak-field asymmetries for the different data sets and resolutions vary quite similarly in time, and their mutual correlations are very high, especially for low-resolution maps, and statistically significant.

### 7.2.4. Weak field shift and fitting ranges

Figure 7.5 shows the shifts for HMI 3600×1440 synoptic map using several different ranges of the weak-field values with the (absolute) upper bound ranging from 1–300 G. Figure 7.5 shows that the shifts have almost the same temporal evolution for all ranges, and that the absolute values vary only slightly. Even as small ranges as 1–5 G yield closely the same pattern. There is hardly any difference at all for range values beyond 7 G as was found in Paper II. This implies that the shifts are determined by values that are very small, close to the maximum of the distribution, which outnumber the large field values and thereby have the largest weight on the Gaussian fit.
Fig. 7.4. Weak-field asymmetries of the six data-sets. Upper panel gives rotational values of weak-field asymmetries obtained from $1800 \times 900$ VSM (blue line), $3600 \times 1440$ HMI (red line), $3600 \times 1080$ MDI (black line), $72 \times 30$ WSO (magenta line), $360 \times 180$ KPVT (green line) and $971 \times 512$ MWO (cyan line) original resolution synoptic maps. The periods of erroneous WSO (from 1996 – 2001.5) and MDI weak-field asymmetry values after 2003 are ignored. Second panel gives the rotational values of weak-field asymmetry of VSM, HMI, MDI, WSO, KPVT, and MWO synoptic maps at $72 \times 30$ resolution. Bottom panel gives the 13-rotation running mean values of second panel. Figure reproduced from Paper II.

7.3. Hemispheric weak-field shifts

In Paper III, we studied the asymmetry (shift) of the distribution of weak-field values separately in the two hemispheres for each synoptic map of photospheric magnetic field. These hemispheric weak-field asymmetries (shifts) were calculated similarly by fitting the histogram distribution of hemispheric weak-field values to a shifted Gaussian. The results of Papers III and IV showed that the shifts in the two hemispheres follow the evolution of the trailing flux, and that the hemispheric shifts have always the same sign as the new polarity of the polar field in the respective hemisphere and solar cycle. In paper III we showed that hemispheric shifts change their sign in the late ascending to maximum phase of the solar cycle and at-
tain their maximum in the early to mid-declining phase, implying that shifts show a strong variation over the solar cycle. Another property of hemispheric shifts, shown in Paper III, is that shifts of the northern and southern hemisphere have opposite sign, but the southern hemisphere shifts are systematically larger in magnitude than in the northern hemisphere. In Paper IV we studied the connection of the hemispheric shifts to the evolution of the poleward surges in more detail, and showed that the maximum of low-resolution hemispheric shifts are typically found when the forward edge of the trailing flux surge reaches the unipolar region of the pole. Figure 7.6 shows the hemispheric shifts for WSO synoptic maps and their relation to the butterfly diagrams of the shifts and of the overall magnetic field.

In Paper IV we also studied the skewness (third moment) of the distribution of the weak photospheric magnetic field values, which depicts quite a different temporal evolution and spatial distribution than the shift. In case of low resolution WSO data the mutual agreement between these two parameters is not very good since skewness has its large maximum around the solar minimum but the shift attains its maximum in the early declining phase. Figure 7.7 depicts the hemispheric

Fig. 7.5. Weak-field asymmetries for 3600×1440 pixel HMI synoptic maps using different (absolute) upper boundaries for the weak-field values from 1–10 G (upper panel) and 10–300 G (lower panel).
weak-field shifts of the field values between -10 G and +10 G and the hemispheric skewness for all field (full-field) values of the WSO synoptic maps. The differences between the two parameters can be understood in that, while the shift is determined only by values around the peak of the distribution, the skewness is much more affected by (a relatively small a number of) the largest field values included within the range of field values.

For high-resolution SOLIS/VSM data (as shown in Paper IV), skewness derived from all field values follow the same temporal evolution and spatial distribution as the weak-field shifts and the large-scale photospheric magnetic field. Skewness then attains its largest values at the flux emergence in mid-latitudes. SOLIS/VSM high-resolution data skewness of the weak field values (within ± 10 G, which was also used to study shift) is very weak everywhere except in the polar regions during the declining to minimum phase of the solar cycle. The distribution of polar weak-field values is always skewed toward zero (weaker absolute values).
Fig. 7.7. Hemispheric weak-field shifts and skewnesses for WSO data.
8. Summary and conclusion

This thesis discusses the spatial-temporal structure and distribution of the photospheric magnetic field. The most important results of the thesis deal with the temporal evolution and the asymmetric distribution of the weak photospheric magnetic field values. In this study of the evolution and asymmetry of the weak field, I have used photospheric magnetic field measurements at Wilcox Solar Observatory (WSO), Mount Wilson Observatory (MWO), Kitt Peak (KP), Synoptic Optical Long-term Investigations of the Sun (SOLIS), Michelson Doppler Imager (MDI) instrument on-board the Solar and Heliospheric Observatory (SOHO) spacecraft, and Helioseismic and Magnetic Imager (HMI) on-board the Solar Dynamics Observatory (SDO) spacecraft. This list of instruments form the large majority of all existing measurements of the photospheric magnetic field ever measured. In order to study the connection between the photospheric magnetic field and the heliospheric magnetic fields, I also used in-situ observations of the heliospheric magnetic field obtained from several spacecraft since the 1960s which are archived in the NASA OMNI database.

In Paper I I studied the spatial structure of the photospheric magnetic field, concentrating on the question of Hale boundaries. Hale boundaries were determined by (nearly) simultaneous HMF sector crossings. I also examined the statistical significance of Hale boundaries. My results showed that the spatial structure of the photospheric field around Hale boundaries and the statistical significance of the corresponding Hale bipolar regions vary significantly with solar cycle, solar cycle phase, and hemisphere. In most cycles, the Hale boundaries of the ascending phase, the maximum, and the declining phase are clear and statistically significant. Overall, the northern hemisphere has a more organized Hale pattern than the southern hemisphere.

In Paper II I studied the asymmetric distribution of the weak photospheric magnetic field values using several data sets. I fitted the histogram distribution of weak field values for each synoptic map of six data sets separately with a parameterized Gaussian function in order to calculate the possible non-zero shift of the weak-field distribution (also called weak-field asymmetry). I estimated the statistical signif-
icance of the weak-field asymmetry for each rotation. I also calculated several versions of lower-resolution synoptic maps from the high-resolution maps and calculated their rotational weak-field asymmetries. Weak-field asymmetries for the different data sets and resolutions vary statistically similarly in time, and their mutual correlations are very high, especially for low-resolution maps. My results also showed that the weak-field asymmetry of high- and low-resolution data have mainly the same orientation, and that the weak-field asymmetries increase with decreasing map resolution. My results give strong evidence for weak-field asymmetries being a real feature of weak-field values, which is best seen in medium- and low-resolution synoptic maps. We suggested that the weak-field asymmetry is most likely related to the supergranulation scale of the photospheric field.

In Paper III I studied the asymmetry values separately in the northern and southern hemispheres. My results showed that the shifts of weak-field field distributions in the two hemispheres have always the same sign as the new polarity of the polar field in the respective hemisphere and solar cycle. I also found that the hemispheric shifts change their sign in the late ascending to maximum phase of the solar cycle and attain their maximum in the early to mid-declining phase. This evolution of the hemispheric weak-field gives a new signal of the solar magnetic cycle.

In Paper IV we studied the latitudinal distribution and temporal evolution of the weak field values in more detail. We found that the weak-field shifts closely follow the evolution of the poleward surges. The surges obtained using low-resolution data have their maxima when the forward edge of the surge reaches the unipolar field region of the polar coronal holes. We also compared the weak-field shifts with the skewness of the weak-field distributions. We found that their temporal evolutions and spatial distributions depict notable differences in case of low-resolution WSO data. The largest differences are found for polar coronal holes, where skewness maximizes due to predominance of one-polarity field values, but the shift remains then smaller than a few years earlier, at slightly lower latitudes. For high-resolution SOLIS/VSM data skewness butterfly diagram resembles magnetic butterfly when using all magnetic field values, but reverses sign when limiting analysis to weak fields (± 10G).

As a whole this thesis presents, for the first time, a detailed study of the spatial distribution and the asymmetric nature of weak photospheric magnetic fields, which are crucial components of solar magnetism. My studies convincingly give a new insight on the evolution of weak fields. I expect that my results advance our understanding on solar magnetism in general, and pave the way to several additional studies on the issues of weak fields in particular.
References


Richardson, I. G., E. W. Cliver, and H. V. Cane, Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high-speed streams, and slow solar wind, *J. Geophys. Res.*, 105, 18, 2000.


