

# **Solar wind – Predicted magnetospheric influence and near-Sun environment**

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# Solar wind – Predicted magnetospheric influence and near-Sun environment

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*“Despite the ‘Dr.’ before his name, he had completed no course of study and received no degree. When people tried to pin him down about this, he would say that the letters were merely an abbreviation of his first name - Drummond - which he did not use. But it was as ‘Dr’ Sam Laserowitz that he appeared in a number of science-fiction magazines; he was also known, in the circles of the fans of that genre, as a lecturer, and spoke on ‘cosmic’ themes at their many conferences and convention. Laserowitz’s speciality was earthshaking discoveries, which he happened upon two or three times a year. [...] We really have no idea what a multitude of con men and crackpots inhabit the domain that lies halfway between contemporary science and the insane asylum.”*

Excerpt from Stanisław Lem 1968, *His Master’s Voice* (Lem & Kandel 1984, p. 38).

## **Abstract**

This thesis analyzes, and derives predictions of how strong solar wind and coronal mass ejections impact the terrestrial magnetosphere and how the solar-wind environment scales in the near-Sun region. Near-Earth in-situ solar-wind measurements, consisting of 35 years of minutely OMNI data, are analyzed together with the time series of the planetary geomagnetic disturbance indicator  $K_p$ . Correlations and functional dependencies are compiled with regard to nowcast the magnitude of the geomagnetic disturbances from in-situ solar-wind measurements and to forecast them from remotely observed solar-wind streams and CMEs. Further, 53 years of hourly OMNI data and sunspot number data are correlated for the purpose of deriving functional dependencies with the state of the solar cycle for the key solar-wind parameters magnetic field strength, proton velocity, density, and temperature. Solar-wind in-situ data from the Helios 1 and 2 missions, operational in the 1970s and orbiting the Sun within the distance range 0.3–1.0 au, are analyzed and empirical solar-wind distance dependencies are derived. Additionally, in view of the planned near-Sun spacecraft mission Parker Solar Probe (PSP) with a planned launch in mid 2018, the solar-wind environment is estimated down to PSP's closest perihelion at 9.86 solar radii.

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# 1 Introduction

## Motivation

thesis goal: finding more precise relationships between parameters/quantities for being able to make better forecasts

catch from chapter abstracts...

This thesis presents quantitative analyses of the solar-wind impact strength on the terrestrial magnetosphere and of the estimated near-Sun solar-wind environment.

I structured this work as follows: In [Chapter 2](#) the fundamentals about the Sun, its activity, solar wind, and space weather are laid. The instruments and data sources are described in [Chapter 3](#). The influences on the  $K_p$  index from solar activity, solar wind, CMEs, and solar-wind streams are analyzed in [Chapter 4](#). In [Chapter 5](#), which is followed by the published paper on the same topic ([Chapter 6](#)), an empirical solar-wind model for the inner heliosphere is developed and used to estimate the near-Sun solar-wind environment for the planned PSP mission. [Chapter 7](#) summarizes the results and gives an outlook for further studies. Useful equations and information are located in the [Appendix A](#).



## 2 Background knowledge

This chapter summarizes the basic knowledge necessary for understanding the analyses performed in this work. First, the Sun's origin, inner structure, atmosphere and heliosphere are described. Then, the Sun's dynamics with its differential rotation and magnetic field generation are outlined. Further, the solar activity cycle is described, including the meridional flow circulation, appearance of active regions, the surface magnetic field change, and sunspot cycles. The heliospheric magnetic field is pictured from its photospheric emergence in magnetic bright points and coronal superradial expansion, through the formation of the heliospheric current sheet and the Parker spiral to the heliosheath. The solar wind and its properties, the origins of slow and fast streams, stream interaction regions, and coronal mass ejections are described. Furthermore, space weather, solar influence on Earth, the magnetosphere, solar wind-magnetosphere coupling, and geomagnetic indices are portrayed.

### 2.1 The Sun

13.8 billion years ago the Big Bang formed our universe. The energy density of our universe consists of 69.1 % dark energy, 25.9 % dark matter and 4.9 % baryonic matter, according to calculations using the inflationary  $\Lambda$ CDM<sup>1</sup> cosmology together with the latest cosmic microwave background temperature measurements (Planck Collaboration et al. 2016). After a few minutes the primordial nucleosynthesis left the universe in a state where the baryonic matter was composed of 75.33 %<sup>2</sup> hydrogen, 24.67 % helium and traces of deuterium, tritium and lithium (Planck Collaboration et al. 2016).

Over millions of years this gas cooled down and gravitationally accreted into molecular clouds and formed stars. The first generations of stars (Population III) fused this gas to heavier elements (metals) and supernovae distributed them into space as a foundation for the formation of new stars of low and high metallicity (Population II and I). Likewise, supernovae of these stars constantly enriched the interstellar medium with metals. Now, the interstellar medium in the Milky Way consists of about 32 % helium and traces of other metals (Danziger 1970).

Our Sun, a metal-rich Population I yellow dwarf star, emerged 4.6 billion years ago (Bahcall et al. 1995) from an accretion disk, formed by a collapsing rotating cloud. The compression within its center resulted in high temperatures, which initiated the fusion of hydrogen to helium (primarily pp chain reaction). The fusion reactions produce huge amounts of energy and heat the solar center to a temperature of 15.7 million kelvins (Christensen-Dalsgaard et al. 1996). The generated energy is transported through the solar body to its surface and eventually into space. The core region extends to about 0.25 solar radii ( $R_\odot$ ), where the declining temperature becomes insufficient for fusion reactions. The energy transport is dominated by thermal radiation until, because of declining ionization and density, at  $0.71 R_\odot$  up to the surface convective motion takes over (Christensen-Dalsgaard et al. 1991).

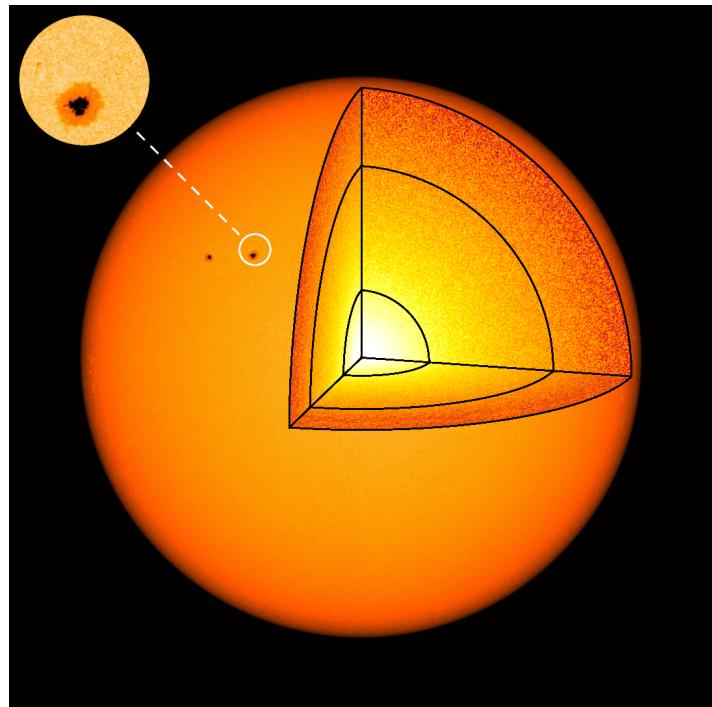
The temperature at this transition region, called tachocline, is about 2 million kelvins and decreases up to the solar surface to between 4400–6600 K<sup>3</sup>. Here at the photosphere, the energy is radiated away with an effective black body temperature of 5772 K (Mamajek et al. 2015), classifying the Sun as a spectral type G2V star. At this surface layer, granules, the tops of convection cells, and temporary sunspots are visible. Strong magnetic flux inhibits the convection at sunspots, leading to lower temperature and brightness (for more on sunspots see the following Sections 2.2 and 2.3). Figure 2.1 illustrates these photospheric features along with the inner solar structure.

Above the photosphere at the base of the chromosphere, the temperature declines to its solar minimum of 3800 K until it raises to 2–3 million kelvins in the corona (Billings 1959; Liebenberg et al. 1975). Up to now it is not fully understood why the corona is so much hotter than the underlying chromosphere – this question is known as the coronal heating problem (Klimchuk 2006; McComas et al. 2007; Fox et al. 2015). The generally considered energy transfer mechanisms are magnetic reconnections, wave heating and type II spicules or a combination of these.

<sup>1</sup> $\Lambda$ CDM: Lambda cold dark matter

<sup>2</sup>Percentages by mass.

<sup>3</sup>NASA Sun fact sheet: <https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html>



**Figure 2.1** Image of the photosphere from 20 March 2016 together with a schema of the solar interior structure. The inset shows the granular surface with a sunspot. I created this figure based on a SDO/HMI continuum image, credit: NASA/SDO and the AIA, EVE and HMI science teams.

The chromosphere is a 2000 km thick region, whose features – numerous spicules, filaments, and prominences – can reach far into the corona. They consist of chromospheric material, channeled by the solar magnetic field, and are enveloped by a thin transition region where the temperature jumps up from about 30 000 K<sup>4</sup> to coronal temperatures. Reconnection of magnetic field lines can result in the eruption of filaments into the corona and beyond, termed coronal mass ejections (CMEs), see also [Subsection 2.5.4](#). Details of chromospheric features are shown in [Figure 2.2](#) – the images were taken on the same day as in [Figure 2.1](#).



**Figure 2.2** Composite image of the solar atmosphere from 20 March 2016 and some details of its features. Corona, chromosphere and photosphere are seen in wavelengths of 193 Å, 304 Å, and continuum. Chromospheric spicules are visible on the northern limb. The enlargements on the right show a prominence and a filament. The dark region at the south pole is a coronal hole. The left inset shows details of the active region belonging to the sunspots shown in [Figure 2.1](#). I created this figure based on SDO/AIA images, credit: NASA/SDO and the AIA, EVE and HMI science teams.

The Sun's atmosphere is dominated by the varying small- and large-scale solar magnetic field configuration. There are regions where the magnetic field lines arc back to the surface and regions with open field lines. In the latter areas the coronal plasma can – guided by the field – escape into space. Thus these coronal areas are less

<sup>4</sup>NASA Sun fact sheet: <https://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html>

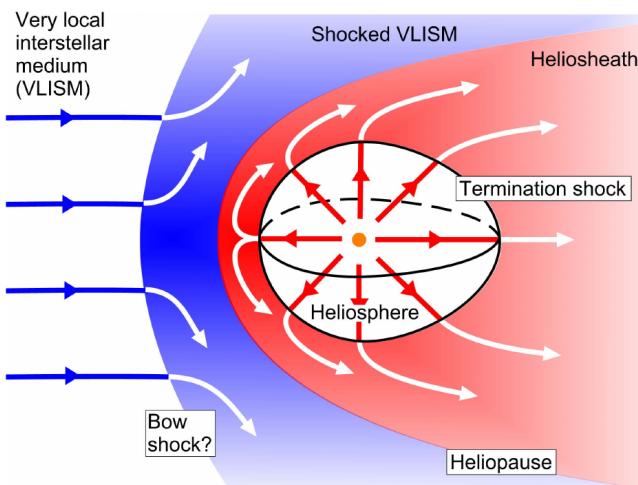
dense, cooler and therefore appear darker in extreme ultraviolet (EUV) and are called coronal holes (CHs). In Figure 2.2 a coronal hole is visible at the solar south pole.

From Earth, the faint corona and chromosphere can only be observed during eclipses, because of the brightness of the solar disk. There are three effects contributing to the visibility of the corona: photons scattering off free electrons, producing a continuous spectrum; photons scattering off dust particles, their spectrum contains Fraunhofer absorption lines; and ion spectral emission lines – these contributions to the corona are termed K-, F- and E-corona<sup>5</sup>. Images from solar eclipses reveal the coronal plasma, shaped by the magnetic field, and red prominences from the chromosphere. The solar eclipse imaged in Figure 2.3 shows the magnetic field's dipole structure and the equatorial streamer belt, characteristic for a quiet Sun during cycle minimum.



**Figure 2.3** Total solar eclipse image of the inner corona up to a distance of five solar radii. The picture was taken in Mongolia, 1 August 2008 and is processed from multiple images. Credit: Miloslav Druckmüller, Peter Aniol, Jan Sládeček, 2008, reproduced with permission.

Due to the high coronal temperatures, plasma escapes the solar gravitational field (Parker 1958) with velocities of  $200\text{--}800\text{ km s}^{-1}$ . Its acceleration is linked to the coronal heating – however, the exact location and process remain an open question (Hollweg 1985; McComas et al. 2007; Fox et al. 2015). The magnetic field becomes too weak to guide the coronal plasma at a distance of a few solar radii. From this so-called source surface, the solar wind flows radially outward into space until it reaches the termination shock. Eventually it collides with the local interstellar medium, creating the boundary of the heliosphere, the heliopause. The heliopause is expected to be a bubble of either teardrop or croissant shape, caused by the Sun's relative velocity of  $23\text{ km s}^{-1}$  with respect to the local interstellar medium (Owens & Forsyth 2013; Opher et al. 2015). Thus, there may exist a leading bow shock. Measurements of the Voyager 1 and 2 spacecraft indicate their passage of the termination shock at about 94 au and 84 au, entering the heliosheath region (Owens & Forsyth 2013). Gurnett et al. (2013) report that in 2012 Voyager 1 actually crossed the heliopause into interstellar space at a solar distance of 121 au. The heliosphere and its surrounding flow structure is illustrated in Figure 2.4.



**Figure 2.4** Schema of the heliosphere and its surrounding flow structure, formed by the interaction of the solar wind (red) with the local interstellar medium (blue) at the heliopause. Credit: Owens & Forsyth (2013, Fig. 9), licensed under CC BY-NC 3.0 DE.

On its way outwards through the solar system, the solar wind – carrying the solar magnetic field – interacts with the planets, their magnetic fields and other solar system bodies. This has various effects, for instance

<sup>5</sup>K from kontinuierlich (continuous in german), F from Fraunhofer, and E from emission.

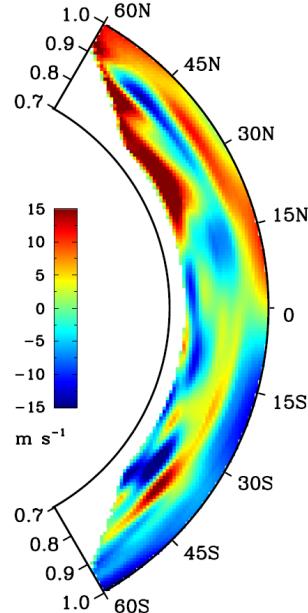
disturbances in planetary magnetic fields with appearance of aurorae and enhanced radiation, atmospheric losses and stripping of cometary tails. Some of these effects can have disruptive consequences for humans and their technology, creating a high interest in understanding space weather and forecasting its effects, the topic of space weather is further addressed in [Section 2.6](#). The magnitudes of these effects depend highly on spatial and temporal variations in the solar wind, which are rooted in the dynamics of the solar magnetic field, described in the following sections.

## 2.2 Solar dynamo

The conservation of the angular momentum in the contracting molecular cloud led to a rotation of the Sun. Although the Sun experiences loss of angular momentum due to solar wind ([Weber & Davis 1967](#)), its rotation still has a current average period of about 25 days. The radial convective motion within the solar interior above the tachocline leads to a transport of momentum away from the rotation axis and therefore to a slower polar and faster equatorial rotation in the convection zone ([Miesch 2005](#)). This differential rotation is visible on the surface and was first discovered from sunspot observations by [Scheiner \(1630\)](#). With a rotation period of about 34 days, the poles have a lag of almost 9 days (for further information on solar rotation see appendix [Section A.1](#)). The differential rotation in the solar interior can be inferred from helioseismological observations. Below the differential rotation of the convection zone, a nearly solid rotation with a period of about 26.6 days (this corresponds to a frequency of 435 nHz) exists in the radiation zone, as shown in [Figure 2.5](#).

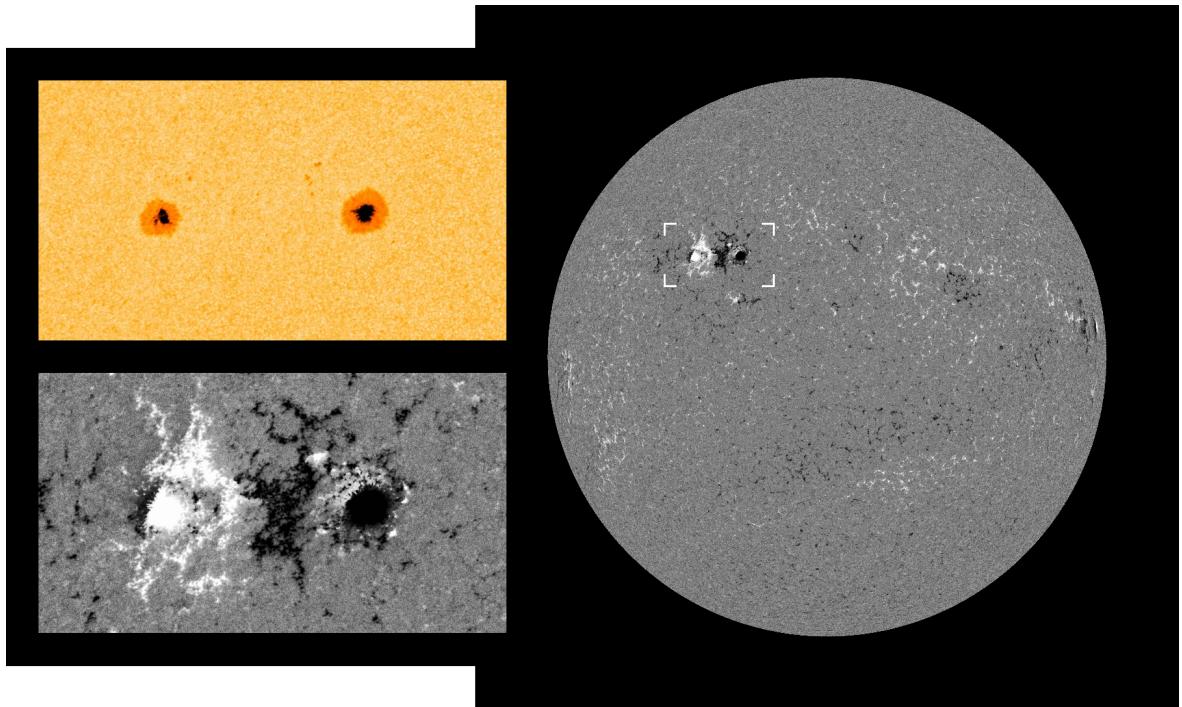


**Figure 2.5** Rotation frequency profile of the solar interior. The location of the tachocline is indicated by the dashed line. The rotation frequency is inferred from helioseismology via observations from the Michelson Doppler Imager (MDI) at the Solar and Heliospheric Observatory (SOHO) spacecraft. Credit: [Thompson et al. \(2003, Fig. 3\)](#), © Annual Reviews, reproduced with permission.



**Figure 2.6** Meridional flow velocity profile in part of the convection zone. Positive values are directed towards north. The velocity is inferred from helioseismology via observations from the Helioseismic Magnetic Imager (HMI) at the Solar Dynamics Observatory (SDO) spacecraft. Credit: [Zhao et al. \(2013, Fig. 4, panel a\)](#), © AAS, reproduced with permission.

Turbulent plasma motions from convective flows in the convection zone generate and carry disorganized magnetic flux. The large rotational shear at the tachocline stretches and amplifies the magnetic fields to strong coherent toroidal flux ( $\omega$ -effect) with intensities of the order 1–10 T. These toroidal fields, generated near the bottom of the convection zone, can be stored in a deep magnetic layer located in the stably stratified region below the convection zone ([Ossendrijver 2003](#)). The stronger flux ropes become buoyant and raise to the surface. The Coriolis force twists them systematically on their way through the convection zone ( $\alpha$ -effect). The twist is stronger at higher latitudes (Joy's law). The flux ropes emerge then in the photosphere as bipolar active regions of opposite magnetic polarity – the stronger ones forming pairs of sunspots, as seen in [Figure 2.7](#). Turbulent convective diffusion of this surface flux contributes to the build-up of poloidal fields. Their resulting polarity is opposite to the prevailing global field due to the directional way the rotational shear at the tachocline



**Figure 2.7** Continuum image of the two sunspots pictured in Figure 2.1 (top left), magnetogram from the same region (bottom left), and magnetogram from the whole solar disk (right). The magnetogram shows the polarity of the line-of-sight magnetic field component at the photosphere (black/white: inward/outward polarity). The highly concentrated magnetic flux at the sunspots is visible as well as the extended bipolar magnetic field structure of the whole active region, which is divided by the so-called magnetic neutral line. The solar disk is scaled to the same size as in Figure 2.1. I created the figure based on SDO/HMI continuum and magnetogram images from 20 March 2016, credit: NASA/SDO and the AIA, EVE and HMI science teams.

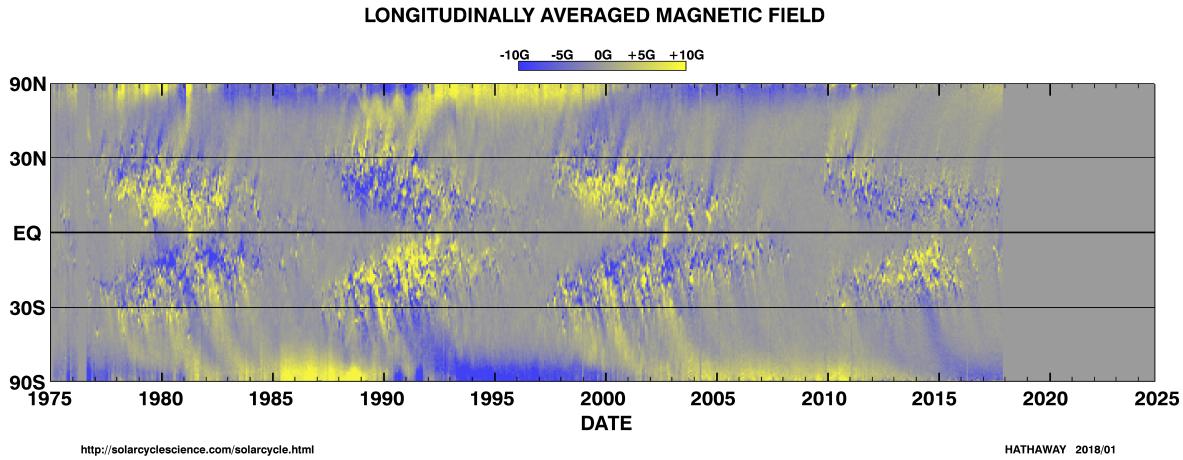
and the Coriolis force in the convection zone act. Fluctuating motions further amplify the mean fields in these processes. This solar  $\alpha\text{-}\omega$ -dynamo is thought to create the major part of the solar magnetic field. Still, with regard to the magnetic field's high variability, the long-term mean fields are governed by intermittent localized structures, that is, active regions, filaments and coronal loops (Miesch 2005).

## 2.3 Solar activity cycle

Helioseismic measurements reveal that the large-scale convective flow is aggregated into large convection cells with slow meridional flows of a few  $\text{m s}^{-1}$ , as can be seen in Figure 2.6. A poleward subsurface flow and equatorward backflow beneath with a further poleward flow below are detected within each hemisphere, comprising a stacked double-cell profile (Zhao et al. 2013). The meridional circulation flow speed has a major influence on the average 22-year period of the emerging magnetic flux at the solar surface. This period varies and is influenced by the stochastic emergence rate and tilts of active regions and the diffusion from random convective motions (Hathaway & Upton 2016). The surface magnetic field configuration changes within one period from a dipole structure to a reversed dipole structure with opposite polarity and back, completing a so-called Babcock-Leighton dynamo cycle. Thus, the transition time from one dipole state to the next lasts about 11 years, this period is defined as one solar cycle.

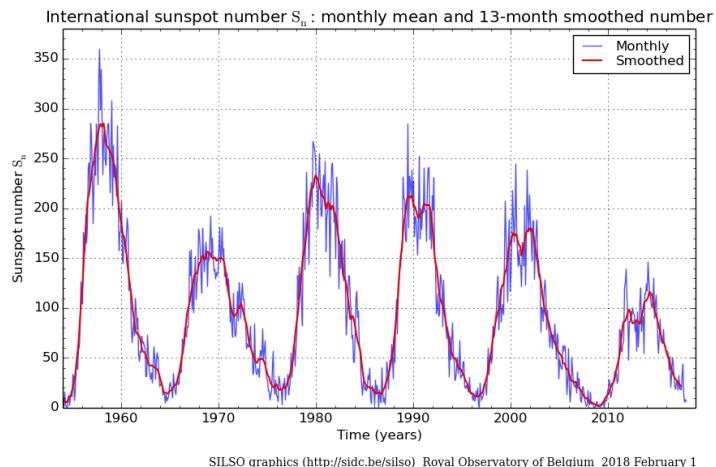
In the transition phase, magnetic flux emerges in belts above and below the solar equator, manifesting as bipolar active regions with sunspots, resulting in a toroidal/multipolar structured magnetic field. Sunspots appear at about  $\pm 20^\circ$  latitude at the beginning of a cycle, this shifts towards lower latitudes at the end of a cycle. Thus the plot of sunspots over latitude and time reveals a butterfly pattern (Maunder 1904). This butterfly pattern appears in surface radial magnetic field observations as well, see Figure 2.8. The leading polarity of bipolar regions is opposite in both hemispheres and the leading polarity changes with each solar cycle, this is called Hale's polarity law. The emerging flux is carried by the slow meridional surface flow poleward, canceling the current dominating polar field polarity and eventually resulting in the polar field switch (Hathaway 2015).

Since regions of strong magnetic flux are visible as sunspots on the photosphere, they were known well before the common era by greek and chinese scholars (Clark & Stephenson 1978; Vaquero 2007). Systematic



**Figure 2.8** Magnetic butterfly diagram of the longitudinally averaged radial magnetic field on the solar surface. Yellow represents an outward directed magnetic field (positive), blue inward (negative). The data is obtained from instruments on Kitt Peak National Observatory and from the MDI at the SOHO spacecraft. Courtesy of David Hathaway, [Solar Cycle Science](#), 2018, updated version of [Hathaway \(2015, Fig. 17\)](#).

sunspot observations exist since 1610, shortly after the invention of the telescope. In 1843 Schwabe discovered the 11-year periodicity in the sunspot occurrence ([Schröder 2004](#), p. 124). In 1848 Wolf introduced the sunspot number (SSN) and the solar cycle number to record these cycles ([Hathaway 2015](#)). The SSN observations, see [Figure 2.9](#), show large variations in cycle length (9–14 years) and cycle amplitude, with peak SSNs in the range 0–300, ([Hathaway 2015](#)). There also exist long-term variations, such as secular cycles of different



**Figure 2.9** Monthly mean sunspot number (blue) and 13-month smoothed monthly sunspot number (red) since 1954. Credit: [SILSO data/image, Royal Observatory of Belgium, Brussels](#), 2018.

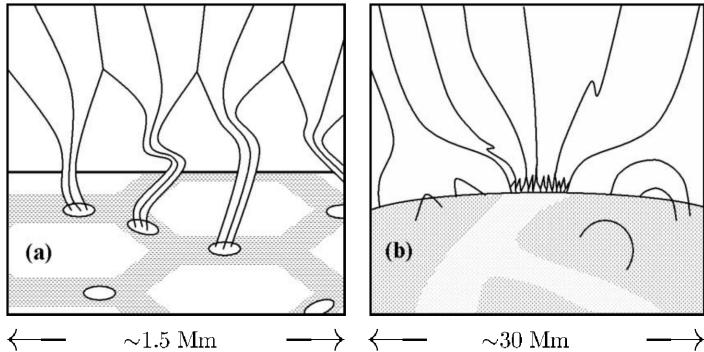
periodicity or the 70-year Maunder Minimum, during which from 1645 on almost no sunspots were observed, ([Maunder 1890](#)). The source of the variations in the solar cycle periods and amplitudes are variations in the meridional circulation, because their fluctuations are larger than those found in the differential rotation and in the convective motions ([Hathaway 2015](#)).

As the SSN is commonly used as an indicator for solar activity, there exists interest in its prediction for the course of the actual and upcoming solar cycles. The continuing prediction of an already commenced activity cycle is reliable, but then the prediction of a cycle before it began is more difficult. Though, there are indications that the polar magnetic field strength during the preceding activity minimum is correlated to the strength of the next solar cycle ([Schatten & Sofia 1987](#)). However, [Hathaway & Upton \(2016\)](#) suggest that the predictability of solar cycles is generally limited – accumulated uncertainty produced by stochastic motions in the convection zone makes predictions further than the next solar cycle very unreliable.

## 2.4 Heliospheric magnetic field

In the quiet Sun during solar cycle minimum, open coronal regions – coronal holes – are the photospheric sources of the heliospheric magnetic field (HMF). Bright points between the granules on the photosphere are

detected in G-band (430 nm) images. They are identified as magnetic flux tubes with field strengths of 100–200 mT (Cranmer & van Ballegooijen 2005). Together, these magnetic bright points (MBPs) cover around 1–2 % of the solar surface and carry many times the flux that active regions do (Sánchez Almeida et al. 2010). These thin flux tubes expand laterally in the low chromosphere and merge to homogeneous network fields, which expand and merge again to a large-scale canopy below the transition region (see Figure 2.10).



**Figure 2.10** Schemata of superradially expanding magnetic flux. (a) MBPs between granules on the photosphere are indicated by ellipses. The protruding lines are thin magnetic flux tubes that merge to a homogeneous network field. (b) Pictured is the network field which expands again to the large-scale canopy field of the lower corona. Credit: Cranmer & van Ballegooijen (2005, Fig. 1), © AAS, reproduced with permission.

The MBPs' convective appearance and stochastic motions on the photosphere result in wavelike fluctuations that propagate upward through the superradially expanding flux tubes. There exist three types of magnetohydrodynamic (MHD) waves within the plasma: compressional fast- and slow-mode waves, and an incompressible wave mode, which is the result of bending magnetic field lines (Alfvén 1942), called shear Alfvén wave. Alfvén waves propagate with a characteristic speed along magnetic field lines. As they transport energy from the photosphere outwards, it is assumed that they play a major role in the coronal heating process and that the solar wind is accelerated up to the so-called Alfvén critical surface at around  $17 R_\odot$ , where the local Alfvén speed equals the solar wind speed (Sittler & Guhathakurta 1999; Exarhos & Moussas 2000). Alfvén waves are dominant in coronal regions that have open magnetic field lines and thus they leak into the fast solar wind (Cranmer & van Ballegooijen 2005). Within solar wind at 1 au, their average velocity is about  $57 \text{ km s}^{-1}$  (Veselovsky et al. 2010) – for more details about the Alfvén velocity see appendix Section A.3.

The coronal plasma in CHs expands superradially, following the magnetic field lines. However, the field strength decreases with increasing solar distance and at a distance of about  $2.5 R_\odot$  the thermal pressure becomes larger than the magnetic pressure. Thereby the magnetic field gets frozen within the plasma and is carried by the solar wind radially outwards into the heliosphere. The distance from which the solar wind propagation gets released from the magnetic field lines is called the source surface (Schatten et al. 1969) and the thermal to magnetic pressure ratio is called plasma beta – for more details on plasma beta see appendix Section A.2. The magnetic field changes from superradial expansion below the source surface to a radial configuration above it, this field geometry is also visible in the total eclipse image in Figure 2.3.

Open field lines expand over adjacent closed field regions. Above the cusps of these regions' closed loops, the surrounding plasma flows encounter each other and stream outwards, forming so-called helmet streamers. Above the helmet streamers, magnetic boundaries are created by plasma flows, carrying opposite magnetic polarity. These boundaries constitute an extensive coronal neutral line around the Sun. Within the heliosphere, the two dominating magnetic polarity regions, originating from both solar magnetic poles, are separated by the extension of this neutral line: a large plasma boundary surface, called the heliospheric current sheet (HCS) (Smith 2001).

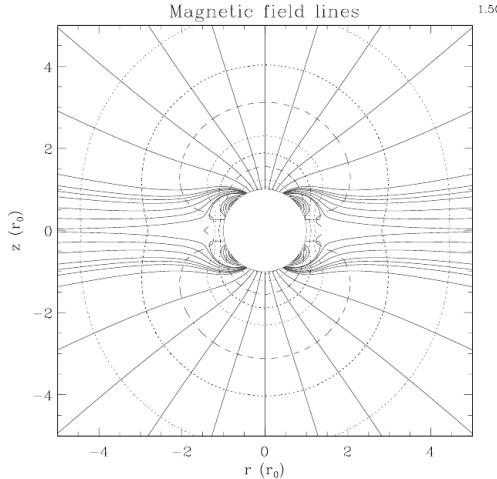
Under solar cycle minimum conditions, the magnetic dipole axis is near the rotation axis and thus the HCS is roughly located near the equatorial plane, dividing both hemispheres. The analytical solar magnetic field model for solar minimum conditions, constructed by Banaszkiewicz et al. (1998), shows this field geometry as seen in Figure 2.11. The quadrupole part of their dipole plus quadrupole plus current sheet (DQCS) model considers the closed equatorial fields and allows equatorial outflow along the current sheet. Commonly around solar minimum, the HCS's warped surface looks like a wavy ballerina skirt, due to the varying tilt angle between the dipole axis and the rotation axis, see Figure 2.12, and also due to local magnetic field variations (Jokipii & Thomas 1981).

During the field transition at solar maximum, the dipole axis rotates to lower latitudes, crosses the solar equator, and eventually the field ends up in a reversed dipole configuration (Jones et al. 2003). During this process, the HCS rotates almost rigidly together with the dipole axis and remains a single connected structure in the inner heliosphere (Jones et al. 2003). Hence during cycle maximum, the HCS has a very complex shape, is largely inclined to the solar equator, and reaches near-polar latitudes.

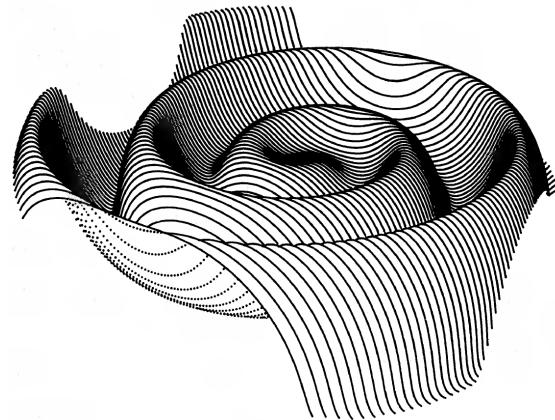
The solar-wind source surface rotates with the Sun and thus shears the HMF into an Archimedean spiral pattern, adding an azimuthal component to the radial HMF. This geometry was anticipated by Parker (1958)

## 2. Background knowledge

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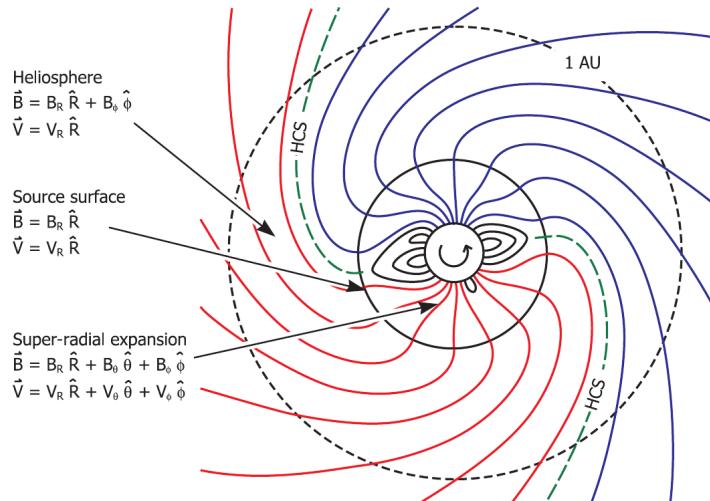


**Figure 2.11** Model of the solar magnetic field geometry in the polar plane for solar cycle minimum. Magnetic field lines (solid) and constant field strength surfaces (dashed) from the DQCS model are plotted. The field line spacing does not represent the field strength but provides better detail where needed. Credit: [Banaszkiewicz et al. \(1998, Fig. 3\)](#), © ESO, reproduced with permission.



**Figure 2.12** A simple HCS model, where its wavy surface shape solely stems from a solar dipole tilt of 15° to the rotation axis. The figure's extent is 25 au across. Credit: [Jokipii & Thomas 1981, Fig. 2](#), © AAS, reproduced with permission.

and is today called Parker spiral. The Parker spiral, viewed in the ecliptic plane, is illustrated in [Figure 2.13](#). The solar rotation axis tilt of up to 7.25° to the ecliptic leads to a slight diving into both hemispheres of opposite polarity. Thus, together with the ballerina topology of the HCS, the Parker spiral has typically a structure of either two or four sectors of alternating magnetic polarity ([Ness & Wilcox 1965](#)), which are separated by the HCS.



**Figure 2.13** Illustration of the Parker spiral formation in the ecliptic plane outside the source surface. The HCS (green) is located between solar-wind flows of opposite magnetic field polarity (red/blue). Credit: [Owens & Forsyth \(2013, Fig. 1\)](#), adapted from [Schatten et al. \(1969, Fig. 1\)](#), licensed under [CC BY-NC 3.0 DE](#).

The just described magnetic structures in the solar wind are overlaid by magnetic clouds (MCs) carried within CMEs. The MC's frequency and magnetic configuration vary with the solar activity cycle. Further, speed differences between solar-wind streams, and between solar wind and CMEs cause enhanced field amplitudes and can result in shocks in the HMF.

That way, the HMF and its structures are carried out to the termination shock by the solar wind. MHD simulations, based on in-situ measurements of Voyager 1 and 2 within the heliosheath and based on IBEX observations of energetic neutral atoms, provide indications about the outer structure of the heliosheath. Behind the termination shock, the magnetic sector boundaries are compressed and they reconnect, forming magnetic bubbles ([Opher et al. 2011](#)). These bubbles – unconnected to the HMF – flow away to the heliosheath tail region. Even beyond the termination shock, the solar-wind plasma seems confined and collimated by the twisted solar magnetic field and driven into a northern and a southern jet ([Opher et al. 2015](#)). Hence, the Sun's magnetosphere has likely a croissant-like shape with two turbulent tail-lobes, where eventually the solar wind

and the HMF are being mixed into the interstellar medium.

## 2.5 Solar wind

It is observed that cometary tails lag a few degrees from the radial direction with respect to the Sun, sometimes they also show fluctuations and become kinked. As such behavior could not be explained by interaction with sunlight pressure, eventually [Biermann \(1951\)](#) concluded that cometary ion tails are influenced by a continuous flow of particles from the Sun. [Parker \(1958\)](#) considered the consequences of Biermann's conclusions and built a solar-wind model, adopting an expanding isothermal solar atmosphere. Parker also incorporated the implications for the solar magnetic field in his model and hence he laid the theoretical foundations for a continuous supersonic radial outflow of magnetized plasma. Thus, the existence of the solar wind was postulated before the first satellites measured it in situ in 1959 ([Gringauz et al. 1960](#); [Neugebauer & Snyder 1966](#)). Since that time, spacecraft are able to measure the solar wind almost continuously with magnetometer and plasma instruments in situ (see [Chapter 3](#)). Pronounced solar-wind structures, such as CMEs and streamers, become visible with the use of space-based coronagraph imagers. From Earth, the outflow of near-Sun solar wind can be observed during solar eclipses, see the eclipse photo in [Figure 2.3](#).

The solar wind is a magnetized plasma consisting of electrons and ions. The ions are mainly composed of hydrogen, a small percentage of helium, and traces of oxygen, carbon, and other metals. The average abundance of helium is about 4.5 % and in slow wind at solar cycle minimum conditions less than 2 % ([Feldman et al. 1978](#); [Schwenn 1983](#); [Kasper et al. 2012](#)). The solar wind is commonly approximated by an ideal incompressible MHD plasma (viscosity  $\mu = 0$  and electrical conductivity  $\sigma = \infty$ ) and can be viewed as a neutral plasma. Also, its helium share is often viewed as being constant, in this case the proton density determines both the helium and electron densities. This work adopts these assumptions and treats the solar wind throughout as a proton plasma.

The properties of solar wind are highly variable in time and space. The key properties are determined by the values of the solar-wind parameters magnetic field strength, proton velocity, density, and temperature. Their average magnitudes scale with solar activity, heliographic latitude, and solar distance. At a solar distance of Earth however, most of the time these parameter's typical values lie in the ranges 3–8 nT, 300–500 km s<sup>-1</sup>, 2–8 cm<sup>-3</sup>, and 10<sup>4</sup>–10<sup>5</sup> K ([Kivelson & Russell 1995](#), p. 92; [Venzmer & Bothmer 2017](#)). The low density of solar wind can be illustrated with a short comparison: 1 liter of air at standard pressure, expanded to a typical solar-wind density of 6.5 cm<sup>-3</sup>, would occupy a volume of a cube with edge length of about 155 km. Solar-wind quantities, such as particle flux densities, mass flux, pressures, and plasma beta, can be derived from the four listed parameters. Having the parameters in the aforementioned ranges, the solar wind is a plasma with a beta mostly greater than unity, that is, the average solar wind carries the HMF and its motions are not influenced by the field direction (for more on plasma beta see appendix [Section A.2](#)).

However, solar wind is structured by its different sources in the solar corona. It consists of fast continuous streams, slow variable flows, and transient CME events. These different flows have highly variable velocities, which result in compressed or rarefied regions at their interfaces. Additionally, the source region's magnetic field configuration organizes the HMF, transported within the solar-wind plasma. Regardless, pronounced magnetic structures embedded in the solar wind, such as field polarity changes or magnetic clouds, still influence the properties of the plasma.

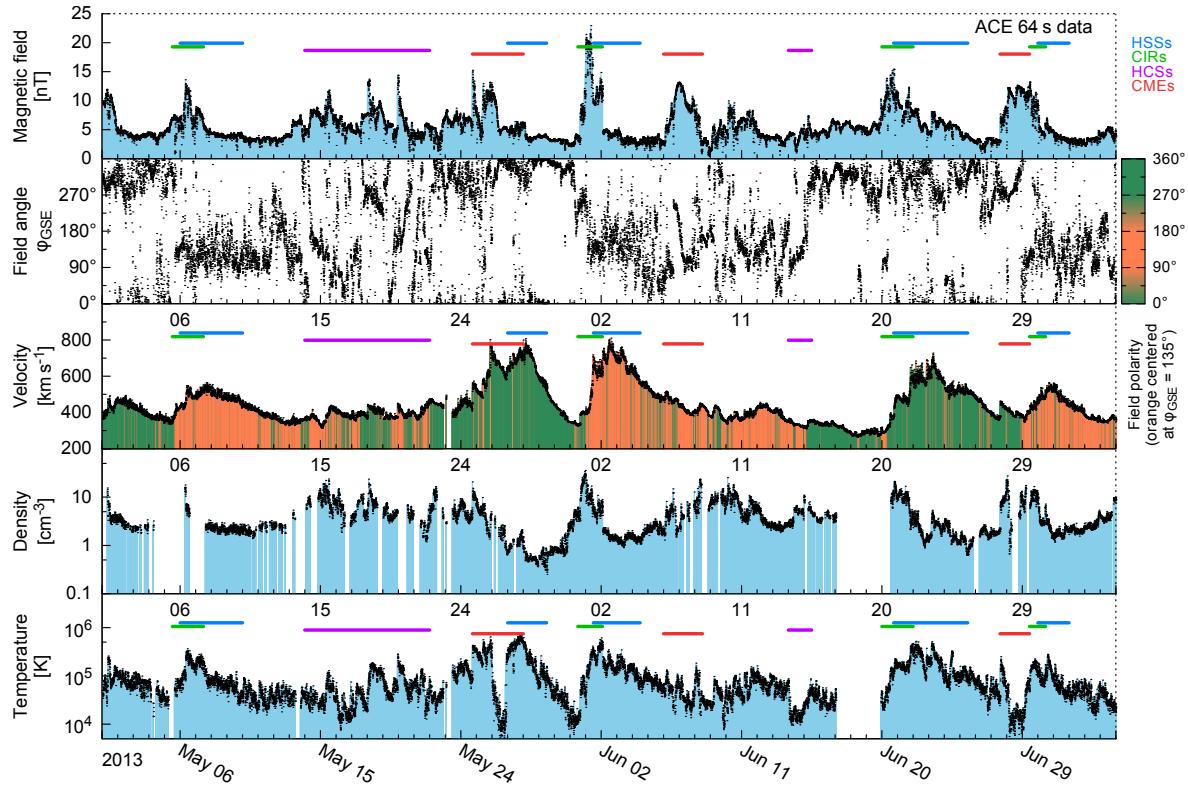
This multitude of structures is apparent in the two months – beginning in May 2013 – of in-situ measured solar wind, which I plotted as an example period in [Figure 2.14](#). The IMF and solar wind ion parameters were measured with the MAG and SWEPAM instruments onboard the Advanced Composition Explorer (ACE) spacecraft, located around the first Lagrange point (L1). The data have a time resolution of 64 seconds and are obtained from the ACE Science Center web interface<sup>6</sup>.

Some general solar wind tendencies can be seen from this plot: The temperature of the solar wind scales with its stream velocity; compressed plasma regions enhance the magnetic field and the density; HCSs, magnetic sector boundaries, and MCs come with high densities and low temperatures; MCs in CMEs have high magnetic fields and low temperatures. I indicated the periods of occurring solar wind structures, that is, HSSs, CIRs, HCSs, and CMEs, with colored bars – these types are further described in the following sections.

There exist a lot more aspects related to solar wind, i.e., MHD waves, the electron pitch angle, solar energetic particles, dust particles, and neutral energetic atoms. Yet, they are not covered here, because their relevance to the analyses in this work is considered minor.

<sup>6</sup> ACE Science Center website: <http://www.srl.caltech.edu/ACE/ASC/>

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**Figure 2.14** Solar wind with several structures, measured at L1 during the time period 1 May to 5 July in 2013. The parameters are the magnetic field strength, its field angle in the ecliptic in GSE coordinates, the proton velocity, density, and temperature. I indicated periods of prominent solar wind structures with color bars: HSSs in blue, CIRs in green, HCSs in purple, and CMEs in red. In the velocity panel also the field polarity is color coded – assuming a Parker spiral angle of 135° at L1. Blank periods indicate bad or missing data. The data are 64 s measurements from the ACE spacecraft.

shocks & MHD waves (Alfvén waves)  
 Alfvén velocity ca. 40 km/s (Kivelson 1995)  
 Alfvén velocity 56.8 km/s (Veselovsky 2009)

sonic and Alfvénic critical point positions (see Sittler & Guhathakurta (1999))  
 sonic point and slow solar wind origin (Sheeley et al. 1997)

### 2.5.1 Slow and fast streams

It is observed at 1 au that the continuous solar wind comes in streams roughly focused at two major velocity ranges (Neugebauer & Snyder 1966; Schwenn 1983), slow and fast streams with 250–450 km s<sup>-1</sup> and 450–800 km s<sup>-1</sup> respectively. Both types possess differences in their typical characteristics and ion compositions. Apart from its higher speeds, fast solar wind has most prominently lower proton densities ( $\sim 3 \text{ cm}^{-3}$ ) and higher temperatures ( $\sim 2 \times 10^5 \text{ K}$ ) than the slow solar wind, which has higher densities ( $\sim 10 \text{ cm}^{-3}$ ) and lower temperatures ( $\sim 4 \times 10^4 \text{ K}$ ) (Schwenn 1990). The fast solar wind has a nature of coming in steady high-speed streams (HSSs) with a unique magnetic field polarity, whereas slow solar wind is much more variable in all its properties except its velocity (Bame et al. 1977). HSSs are further overlaid with Alfvén waves, which modulate the stream velocity with typical periods of 15–60 min.

First soft X-ray observations of the corona, made during sounding rocket flights in the early 1970s, showed clearly that the fast solar wind emerges from extended areas of reduced X-ray emission, subsequently called coronal holes (CHs) (Krieger et al. 1973; Hundhausen 1977). The magnetic field polarities found in CHs are associated with the magnetic field directions observed in HSSs, as seen in Figure 2.15. In coronal regions with closed magnetic field lines, the plasma is trapped, though in CHs it can escape, following the open magnetic field lines outwards into space. Wave-particle interactions heat and accelerate the ions in CHs, leading to the emission of a fast solar wind (Hollweg & Isenberg 2002). Superradial expansion of the magnetic field lines in the corona has an influence on the wind speed – actually the expansion factor is anticorrelated with the final



**Figure 2.15** Solar-wind velocity with respect to its estimated source longitude (top) and coronal brightness contour map at  $0.5 R_{\odot}$  above the photosphere (bottom) for the Carrington rotation 1616. The velocity is based on IMP spacecraft data, back-extrapolated to  $20 R_{\odot}$ . Brightness values below a fixed threshold are shaded corresponding to the magnetic field polarity (+/-) of the underlying photosphere. The map is based on observations from the K-coronameter at the Manua Loa Observatory. Credit: Hundhausen (1977, Fig. 10), © Colorado Associated University Press, get permission...

wind velocity (Wang & Sheeley 1990). As the field expansion is larger near the border of CHs, faster wind emerges from the mid regions of CHs, forming into HSSs. However, there are indications that the slow and fast solar wind are not only generated at different sources but from distinct mechanisms (McGregor et al. 2011a).

The high variability in the slow solar wind points to the existence of different types of slow wind flows, originating from separate coronal locations and mechanisms (Schwenn 1983). It is still under debate if the variability is produced by the formation mechanism of the slow solar wind or if the variability is caused during the acceleration/propagation phase (Sanchez-Diaz et al. 2016). Still, at least a part of its variability can be attributed to the interactions between slow and fast solar wind, which result in a general reduction in velocity differences and thus let solar winds of different speeds (having different properties as well) converge to a common intermediate speed regime in the range  $400\text{--}500 \text{ km s}^{-1}$  (McGregor et al. 2011b; Sanchez-Diaz et al. 2016). Studies using remote white-light tracing of coronal material and in-situ measurements of solar wind suggest that multiple sources of slow solar-wind flows exist (Wang et al. 2000; Kilpua et al. 2016). To the best of my knowledge, the generally considered sources are listed in the following:

- CH boundaries and small CHs, because their plasma outflow is slower due to the high superradial expansion of its open field lines (Wang & Sheeley 1990).
- CH boundaries, when trapped plasma is released by reconnection between open and closed field lines (Madjarska et al. 2004).
- Helmet/pseudo-streamers in active regions, where transient plasma blobs are released from the cusps of closed field loops (Wang et al. 1998, 2000). This slow and dense material is associated with the heliospheric plasma sheet belt.
- Edges of active regions, which have hot plasma outflows with a single magnetic polarity (Kojima et al. 1999).
- Jets originating from coronal bright points might contribute to the slow solar wind (Subramanian et al. 2010).
- Slow unidentified CMEs can be a source of slow wind as well.

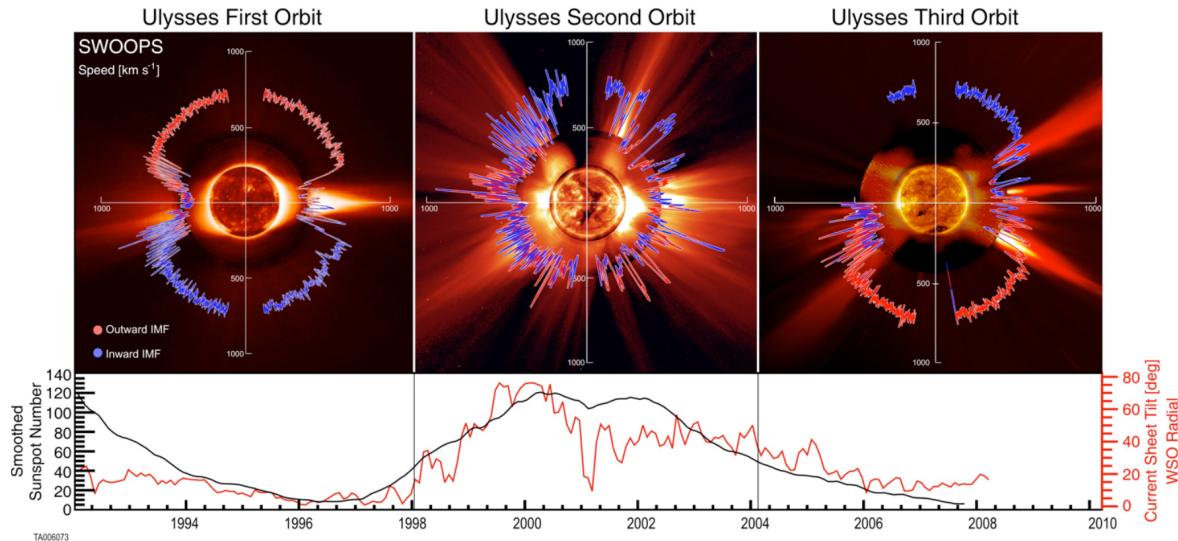
It is found to be difficult to use in-situ measurements for tracing the slow solar-wind flow types to different origins and distinguishing between them, because most properties are also highly variable in time (Kilpua et al. 2016). However, some indicators show tendencies to differentiate between the slow winds from different source regions. Some notable indicators are: elemental ion ratios, heavy ion charge states, and the specific entropy.

The elemental composition of the coronal plasma varies with height/location in the solar atmosphere, therefore the solar wind's elemental ion ratios (e.g., He/H, Fe/O) are used to determine its origin. The charge states of coronal heavy ions depend on the local temperature. However, the density of the outwards expanding plasma decreases fast, preventing further ionization/recombination. The charge states decouple from the local temperature and freeze in still close to the Sun. Thus, heavy ion charge ratios (e.g.,  $\text{C}^{+6}/\text{C}^{+4}$ ,  $\text{O}^{+7}/\text{O}^{+6}$ ) in the solar wind track the coronal source temperature and especially the  $\text{C}^{+6}/\text{C}^{+4}$  ratio is sensitive to the solar-wind

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type (Landi et al. 2012). At solar minimum the specific proton entropy is found to correlate with the  $O^{+7}/O^{+6}$  ratio and thus able to trace slow solar-wind sources as well (Pagel et al. 2004).

The solar-wind stream pattern varies strongly with solar activity. The Sun's ordered dipole structure during solar cycle minima leads to polar regions with open magnetic fields, constituting large coronal holes, and to a large equatorial belt region with closed magnetic fields – this state is clearly visible in Figures 2.3 and 2.11. This state results in fast solar wind coming exclusively from the poles and higher latitudes, whereas active regions form an equatorial streamer belt around the Sun, emitting slow solar wind. This structure was confirmed from solar-wind speed measurements done by the Ulysses spacecraft, which flew in an out-of-ecliptic solar orbit and whose mission covered a duration of more than one solar cycle (McComas et al. 2008), see Figure 2.16. The transition of the solar magnetic field during the solar cycle maxima induces the chaotic appearance of



**Figure 2.16** Solar-wind velocity and magnetic field polarity (red/blue) with respect to heliographic latitude for the three orbits of the Ulysses spacecraft during low and high solar activity (upper panels). The data starts top left and runs counter-clockwise. The corresponding smoothed SSN (black) and HCS tilt angle (red) are plotted beneath. The background consists of solar images for solar cycle 22 minimum (1996-08-17), solar cycle 23 maximum (2000-07-12), and solar cycle 23 minimum (2006-03-28). The solar disk, inner corona, and outer corona images are from SOHO/EIT (Fe XII at 1950 nm), Mauna Loa K coronameter (700–950 nm), and SOHO/C2 white light coronagraph. Credit: McComas et al. (2008, Fig. 1), © American Geophysical Union, reproduced with permission.

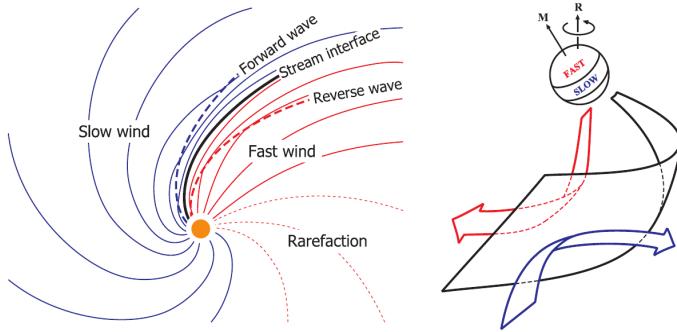
closed magnetic fields at higher latitudes and even at the poles. Further, coronal holes begin to invade parts of the equatorial region, this leads to recurring phases of HSSs in the ecliptic. This can be seen from the solar-wind period in Figure 2.14, where recurrent HSSs of the same field polarity but changing peak velocity exist – beginning on 6 May, 2 June, and 29 June 2013. The succeeding streams of different velocity result in interaction regions and alternating magnetic polarities result in magnetic sector boundaries.

### 2.5.2 Stream interaction regions

The sources of the slow and fast solar wind rotate together with the Sun. Their uneven distribution on the solar surface – due to a significant inclination of the dipole axis or variations of the solar magnetic field – lead to the alternation of slow and fast wind streams that flow into the heliosphere (Owens & Forsyth 2013). In case of a fast stream being followed by a slow stream, a rarefaction region expands at their interface. If it is the other way around, the stream of fast solar wind catches up to that of slow wind ahead of it and a compression region forms at their interface, which is encompassed by two compressional waves (Balogh & Jokipii 2009). The latter are stream interaction regions (SIRs) and they take the shape of spiral fronts, as seen in the left panel of Figure 2.17.

When the solar dipole field is in a quasi-stable configuration, SIRs can stay for multiple solar rotations, recurrently sweeping over the heliosphere in 27-day periods (Gosling et al. 1972). Hence, they are referred to as co-rotating interaction regions (CIRs) (Smith & Wolfe 1976; Balogh et al. 1999). Around 1 au, CIRs occur commonly during the declining phase of the solar cycle when polar CHs form equatorial extensions (Balogh & Jokipii 2009).

The spiral shape of the stream interfaces and their inclination to the solar rotation axis lead to a deflection of



**Figure 2.17** Schemata of the formation of a stream interface (left) and the deflection of streams along the interface (right). The stream interface (black) is located between regions of slow (blue) and fast (red) solar wind. Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2), licensed under CC BY-NC 3.0 DE.

both streams (Balogh & Jokipii 2009). Due to the fast and slow streams' collision, the fast wind is decelerated and the slow wind is accelerated and their flow directions are systematically deflected away from the interface, as shown in the right panel of Figure 2.17.

The plasma pressure inside CIRs is increasing with heliocentric distance and therefore, the leading and trailing compressional waves form into forward and reverse shocks – typically at solar distances between 2–10 au (Smith & Wolfe 1976; Balogh & Jokipii 2009). The solar-wind speed increases abruptly at both shock fronts. With increasing solar distance, the leading and trailing shock fronts travel away from the stream interface. This widens the interaction regions and eventually they gain on the close-by interaction regions (Burlaga et al. 1984). Beyond 10 au they fuse to merged interaction regions (MIRs), which are narrower and more compressed (Burlaga et al. 1985).

Due to the compression within SIRs/CIRs, the magnetic field strength and the plasma density are higher than in the ambient streams. These signatures can be seen in the in-situ solar-wind plot in Figure 2.14. The CIRs on 5 May, 1 June, and 29 June 2013 are followed by recurrent HSSs and they contain sector boundaries as well. They are not yet accompanied by strong shocks owing to the measurement location at 1 au.

### 2.5.3 Heliospheric current sheet

The HCS, the boundary surface between solar-wind streams of opposite magnetic polarity, is formed by open magnetic fluxes, expanding from both sides over closed field regions and coming into contact above. At the boundary between open and closed fields, local coronal plasma gets released and flows slowly between the fast wind streams along the current sheet into the heliosphere, creating a helmet streamer. This is why near the Sun, the HCS is typically located within slow solar wind stemming from the coronal streamer belt Owens & Forsyth (2013). However, with increasing solar distance, the shock wave of the adjacent SIR/CIR can pass the HCS, so that sector boundaries are often found to be embedded within SIRs/CIRs (Gosling & Pizzo 1999).

Sector boundaries in the solar wind are observed in situ, they come with significant depletions in  $\text{He}^{++}/\text{H}^+$  values (Borrini et al. 1981). The other solar wind parameters, such as velocity, density, and temperature, change with distance from the HCS as well (Smith 2001). The HCS region itself is quite narrow with a thickness of around 3000–10 000 km; it is embedded in a region of 20–30 times its thickness, the heliospheric plasma sheet (HPS) (Winterhalter et al. 1994). The HPS contains the magnetic polarity reversal and is of low magnetic field strength and high density, resulting in a significantly enhanced value of plasma beta (Crooker et al. 2004). In the slow solar wind, the HPS can also be identified from its particularly low specific entropy, arising from its low temperature and high density (Kilpua et al. 2016).

### 2.5.4 Coronal mass ejections

Using SOHO LASCO, EIT, and MDI and ground-based  $\text{H}\alpha$  data, Cremades & Bothmer (2004) concluded that a simple scheme can be used to relate CME white-light topology to the heliographic position and orientation of the underlying magnetic neutral line.

When the neutral line is approximately parallel to the solar limb, the CME appears as a linear feature parallel to the limb having a broad, diffuse inner core. When the neutral line is approximately perpendicular to the solar limb, the CME is observed along its symmetry axis, and the core material lies along the line of sight. Joy's law implies that the frontside neutral line will typically lie perpendicular to the east limb and parallel to the west limb. The neutral line and CME orientations are reversed for the solar backside, so backside CMEs are viewed predominately orthogonally to frontside CMEs at each limb (?).

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During the eruption of the flux rope it may or may not undergo considerable distortion depending on the level of complexity of its evolution ([Cremades & Bothmer 2004](#)).

There is a large range in the basic properties of CMEs, although some of this scatter is likely due to imaging projection effects (e.g., Burkepile et al. , 2004; ([Cremades & Bothmer 2004](#))).

The real axis of the CME seems to correspond with the long axis of a large-scale helical magnetic flux rope that was formed in the SR, with the prominence being the bottom part of this magnetic system ([Cremades & Bothmer 2004](#)).

Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) on board the Solar Terrestrial Relations Observatory (STEREO) spacecrafts ([Howard et al. 2008](#))

CME kinematics with velocity and acceleration determined from remote observations  
early CME deceleration: The results by [Sachdeva et al. \(2017\)](#) indicate that due to solar-wind drag, the speeds of fast CMEs will commonly slow down substantially from early distances of a few solar radii. paperMVVB

Much higher or lower peak values at 1 au have been observed in extraordinary events, such as the 23 July 2012 CME with a speed of over  $2000 \text{ km s}^{-1}$  and a peak field strength of about  $100 \text{ nT}$  that was observed by STEREO A ([Russell et al. 2013](#)). paperMBBV

The maximum speed exceeds  $3000 \text{ km/s}$ , but only in a couple of cases. About 50 CMEs had a speed exceeding  $2000 \text{ km/s}$  (Solwind detected only one CME with a speed of  $2000 \text{ km/s}$ ). [Gopalswamy et al. \(2010\)](#) suggested that one does not observe CMEs with speeds exceeding  $4000 \text{ km/s}$  because of the limit on the maximum free energy that can be stored in solar active regions. The limit was estimated to be  $\sim 10^{36} \text{ erg}$  assuming a hypothetical active region with the largest area ever observed containing the largest magnetic field strength ever observed in sunspots. A single CME usually does not exhaust all the available free energy. The largest kinetic energy observed was  $1.2 \times 10^{33} \text{ erg}$  for the Halloween 2003 CME on October 28 ([Gopalswamy et al. 2005](#)). This study suggests that the speed of CMEs may not be much higher than  $3000 \text{ km/s}$ , consistent with the free energy available in active regions. An important practical implication of such a speed limit is that the Sun-Earth travel times of CME-driven shocks may not be less than 0.5 day ([Gopalswamy et al. 2005](#)). From these results, one can infer that CMEs may not have speeds far greater than  $3000 \text{ km/s}$ . This speed limit has a practical implication that CME-driven shocks take at least half a day to reach Earth after their launch at the Sun ([Gopalswamy et al. 2005](#)).

There are still unresolved questions: do CMEs without flux rope exist? the connection between flux ropes observed in the corona and measured in situ is not fully understood ([Vourlidas 2014](#)).

Are there any CMEs that are not FR-CMEs? ([Vourlidas et al. 2013](#)).

unresolved questions: predicting when a CME will occur on the Sun, and when it will arrive at a given destination in the heliosphere and what its magnetic structure would be in situ ([Gopalswamy 2016](#))

There still exist multiple models for release and acceleration mechanisms.

active regions: sunspots, magnetic reconnections, flares, post-eruptive arcades, coronal dimming  
by-products of coronal magnetic instability  
The solar differential rotation wraps the magnetic field lines, accumulating tension, leading eventually to relief with a magnetic reconfiguration by field line reconnections.  
-> release of much energy -> flares, CMEs  
flares and SEPs often accompany CMEs

solar energetic electrons (SEPs)  
[Kahler et al. \(1978,1983\)](#) found a good correlation between the CME speed and SEP intensity. These authors concluded that 'energetic protons are accelerated in the shock front just ahead of the expanding loop structures observed as mass ejections.' This result formed the basis for the establishment of shock acceleration as the leading mechanism for SEPs ([Cliver et al. 1982; Cane et al. 1988; Gosling 1993; Reames 1995](#)).

It has been known for a long time that the orientation of interplanetary flux ropes are generally aligned with the polarity inversion line (PIL) (or filament) at the Sun ([Marubashi 1997; \(Bothmer & Schwenn 1998\); Yurchyshyn et al. 2001; Marubashi et al. 2009](#)).

Recently, [Marubashi et al. \(2015\)](#) analyzed a set of more than 50 well observed CME-ICME pairs and found strong support to the idea that an erupted flux rope has its main axis parallel to the polarity inversion line and

remains so as it propagates through the interplanetary space.

Strong support of the idea that a flux rope with the main axis parallel to the PIL erupts in a CME and that the erupted flux rope propagates through the interplanetary space with its orientation maintained and is observed as an IFR ([Marubashi et al. 2015](#)).

In fact the deflection could be in any direction, depending on the relative position of the coronal hole and the eruption region (Cremades et al. 2006; Gopalswamy et al. 2001).

The physical reason for the deflection has been shown to be due to the global magnetic pattern surrounding the eruption region (Filippov et al. 2001; ([Sterling et al. 2011](#)); Gui et al. 2011; Panasenco et al. 2013; Kay et al. 2013; Möstl et al. 2015).

the arrival of CMEs at 1 AU gets delayed when they interact with preceding CMEs ([Manoharan et al. 2004](#)); ([Temmer et al. 2012](#)).

A solar radio burst is a structure in frequency space that changes with time.  
 type II radio burst (drift to low frequencies): fundamental and second-harmonic bands; evidence for shocks in the corona, rendered visible by the radiation of electrons that they accelerate. There is almost always a delay between the flare onset and the start of Type II emission. the shocks that produce Type II bursts are maybe always being driven by CMEs

type III radio burst (spikes): parallel to flares; track electron beams through decreasing sw plasma density along Parker spiral; frequency scales with distance

type IV radio burst: roadband quasi-continuum features associated with the decay phase of solar flares. They are attributed to electrons trapped in closed field lines in the post-flare arcades

significant correlation between the occurrence rate of CMEs and the sunspot number ([Hildner et al. 1976](#)) (they used Skylab coronagraph observations and SSN).

Their rate follows the solar activity cycle and varies in near 1 au measurements between only one CME every couple of days during solar cycle minima up to multiple CMEs observed over several days at times of solar maxima, that is, the CME-associated flow share of the solar wind raises from about 5 % up to about 50 % ([Richardson & Cane 2012](#)). paperMVVB

CME occurrence rate was found to track the solar activity cycle in both amplitude and phase (([Webb 1991](#)); [Webb and Howard 1994](#)).

Their frequency in near 1 au measurements varies between almost zero during solar cycle minima up to a daily rate of about 0.5 during times of solar maximum ([Richardson & Cane 2012](#)).

historical CME review by [Gopalswamy \(2016\)](#).

historic review; [Syun-Ichi Akasofu2011](#)

, called interplanetary CMEs (ICMEs)

observed coronal transient: 3d structure, directed at Earth, associated with shock wave; ([Howard et al. 1982](#))  
 -> halo CME

([Gosling et al. 1986](#)): bi-directional electrons in CMEs

CME-plasma parameter values

## 2.6 Space weather

Solar wind influences the terrestrial magnetosphere and can disturb sensitive technical systems.  
 Understanding its properties helps with the prediction of geomagnetic storm events.

various space weather effects, for instance disturbances in magnetic fields, aurorae, episodes of enhanced radiation, atmospheric losses and stripping of cometary tails. figures of these effects?

influences on human infrastructure/technical systems/animals (such as birds and whales -> Vanselow2017  
 10.1017/S147355041700026X)

## 2. Background knowledge

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reference to [Bothmer & Daglis \(2007\)](#), maybe images

Space weather effects can be directly attributed to CME sub-structures. While the outermost structure (shock) accelerates particles and causes sudden commencement, the interior structures (sheath and flux rope) cause geomagnetic storms if they possess a strong southward component of the magnetic field ([Gopalswamy 2016](#)).

see Wing K<sub>p</sub> model description...

### 2.6.1 Solar influence on Earth

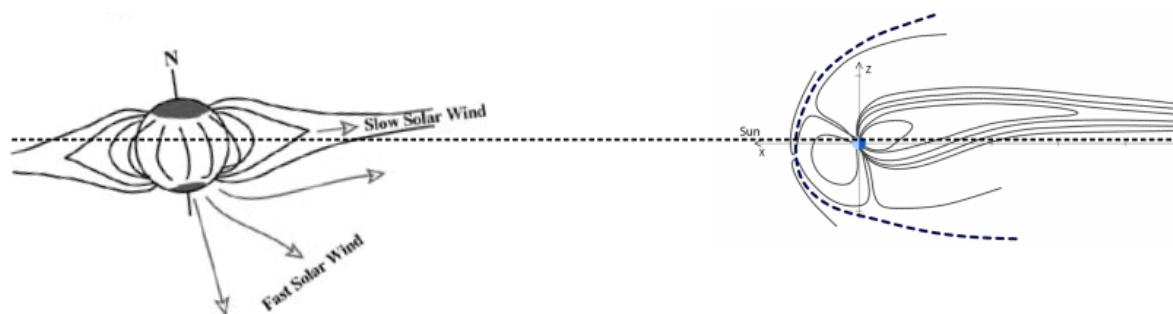
solar wind's impact on Earth

Carrington made first connection between terrestrial magnetic field and solar flares. correct?

there are several types of solar-terrestrial relations, [Bartels \(1962\)](#) listed:

- a) irregular flare and CME effects (Carrington)
- b) 11-year solar cycle effects
- c) 27-day solar rotation effects
- d) daily Earth rotation effects (Xray and light)

seasonal effects from Earth orbital distance, inclination (solar rotation axis angle) and Earth tilt (see [Figure 2.18](#))



**Figure 2.18** Sun-Earth geometry in the plane orthogonal to the ecliptic (not to scale); Solar magnetic field-magnetosphere geometry. Seasonal effects are: solar tilt, Earth distance and Earth tilt. make new figure, see Hundhausen1977, p. 285...

solar wind and its structures

solar radiation

solar energetic particles (SEPs)

gravitation

magnetosphere

ionosphere?

aurorae

geomagnetic storms (several days, from CMEs)

substorms (few hours, from CIRs??)

see Akasofu2011

for humans and their technology important effects: enhanced radiation, geomagnetic storms  
lovely, disruptive, dangerous consequences <- read in VBbook

at Earth the solar wind total energy flux ( $1.45 \text{ mW/m}^2$ ) is only about one millionth of the solar radiation flux (see [Schwenn \(1990, p. 153\)](#))

"The principal users affected by geomagnetic storms are the electrical power grid, spacecraft operations, users of radio signals that reflect off of or pass through the ionosphere, and observers of the aurora."NOAA cite

X ray fluxes from flares are also responsible for producing sudden, short-lived enhancements in the electron content of the ionosphere (TEC), known as sudden ionospheric disturbances. cite from Gosling1993

[Carrington \(1859\)](#) observed a brightening on the Sun on 1 September 1859 and noted a strong geomagnetic storm that occurred 17 hours later.

Forbush1937 found the rapid reduction in cosmic ray intensity (Forbush decrease) during geomagnetic storms (caused by CMEs).

[Gosling \(1993\)](#) pointed out that the emphasis on flares is misplaced as far as geomagnetic storms and large SEP events are concerned and he referred to this as 'solar flare myth'. [Gosling \(1993\)](#)'s conclusions represented the culmination of research on CMEs in the 1970s and 1980s bringing them to the forefront as the main players in affecting Earth's space environment.

Coronal mass ejections have the central role in the chain of events leading from the Sun to near-Earth space (relationship between solar activity and interplanetary and geomagnetic events) ([Gosling 1993](#)).

Coronal mass ejections (CMEs) have been established as the primary source of major geomagnetic storms and large solar energetic particle (SEP) events ([Gosling 1993](#))

The weaker solar activity cycle 24 seems to have important consequences for CMEs in the heliosphere: CMEs expand anomalously due to reduced heliospheric pressure leading to the increased observed rate of small CMEs, halos originating far from the disk center, and mild space weather (([Gopalswamy et al. 2014](#)), [2015a](#); Petrie 2015).

The total pressure in the heliosphere (magnetic + plasma) is reduced by ca. 40%, which leads to the anomalous expansion of CMEs explaining the increased slope. The excess CME expansion contributes to the diminished effectiveness of CMEs in producing magnetic storms during cycle 24, both because the magnetic content of the CMEs is diluted and also because of the weaker ambient fields ([Gopalswamy et al. 2014](#)).

## 2.6.2 Magnetosphere

the name magnetosphere was proposed by [Gold \(1959\)](#)

The cavity is called the magnetosphere. It has a relatively well-defined outer boundary, the magnetopause.

The magnetosphere's shape is formed by the dynamic pressure balance. The structure is similar to the heliosphere in the ISM.

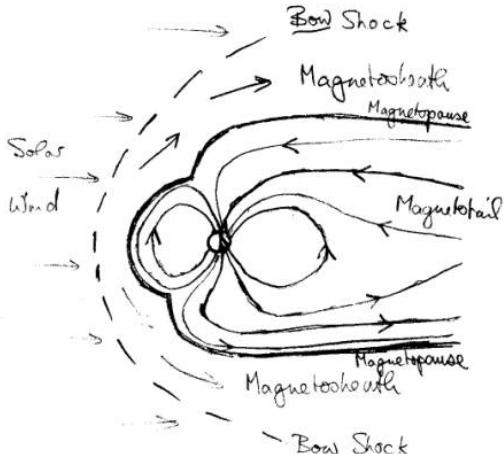
bow shock, magnetotail, magnetosheath, magnetopause  
add ecliptic and terrestrial tilt angle; with plasmoid?  
see [Figure 2.19](#)

turbulence with sw (KH or RT instabilities)

Earth magnetic field strength at a height of 36 000 km (geostationary):  $\approx 100 \text{ nT}$   
Earth magnetic field strength at the surface - equator:  $\approx 30\,000 \text{ nT}$  - poles:  $\approx 60\,000 \text{ nT}$  (cite?)

The critical connection between CMEs and geomagnetic storms was made by [Wilson \(1987\)](#), who found that the southward component of the magnetic field in magnetic clouds is responsible for the storms. [Wilson \(1987\)](#) performed a superposed epoch analysis of 19 magnetic clouds and found that the Dst index simultaneously decreased to a large negative value at the onset of a large, sustained southward magnetic field in the magnetic cloud; the storm recovery started when the magnetic field turned northward.

Results from this study clearly show that magnetic clouds (bubbles) are associated with geomagnetic storms and that the association is statistically significant. [Wilson \(1987\)](#)



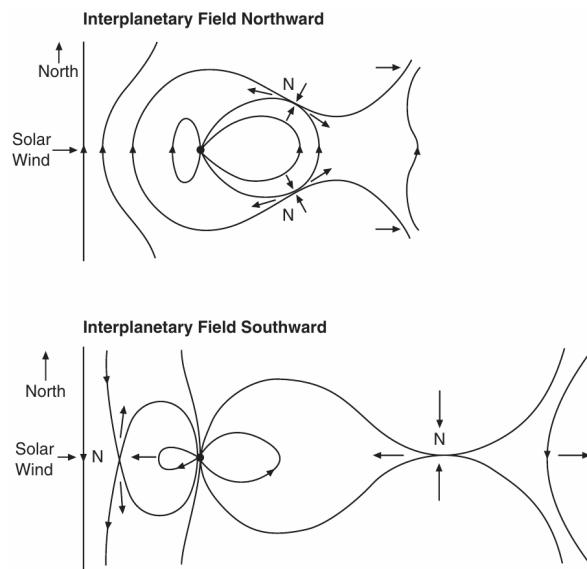
**Figure 2.19** temp figure...

Predicting the magnetic field variations in ICMEs from solar observations is a central subject for space weather forecasting because a long-lasting southward-directed field is a primary driver of major geomagnetic storms ([Zhang et al. 2007](#)).

88 major geomagnetic storms: single ICME, multiple ICME, and CIR events; numbers 53 (60%), 24 (27%), and 11 (13%) ([Zhang et al. 2007](#)).

magnetopause = current layer??

two extreme cases of  $B_z$  orientation: parallel/antiparallel compression/reconnection (see [Figure 2.20](#))



**Figure 2.20** reconnection and compression depending on the interplanetary magnetic field orientation.  
Credit: [Bothmer & Daglis \(2007, p. 116, Fig. 4.8\)](#), adapted from Dungey 1961, 1963. get permission... accelerated flows are arrowed; N points are X points...

standoff distance: ([Bothmer & Daglis 2007](#), p. 112)

$$d = \frac{107.4}{1R_E} (NV^2)^{-1/6} \quad (2.1)$$

Even in “ancient” times (when?) a correlation between solar particles and disturbances in the magnetosphere were known of (Bartels 1962).

magnetosphere variations due to solar wind  
magnetosphere protects from radiation (maybe from solar wind stripping atmosphere away?)

effects: aurorae, ...

ring current systems

definition of:

magnetic storm...

substorm...

subsection Ionosphere?

its variations due to solar radiation (day/night cycle and flares)

ionosphere -> TEC -> GNSS error

Solar wind interaction processes with the magnetosphere:

there are several underlying physical mechanisms, whose contribution is not yet quantified'?

physical mechanisms:

- reconnection
- compression
- turbulence
- induction?

three ways for solar wind momentum and energy transfer into magnetosphere:

- sw entering sphere
- waves/eddies
- reconnection

### 2.6.3 Solar wind–magnetosphere coupling

R-M effect:

E-field produced by solar wind: acts on magnetospheric plasma

$$\mathbf{E}_{\text{IMF}} = -\mathbf{V} \times \mathbf{B}_{\text{IMF}} \quad (2.2)$$

from Lorentz force  $\mathbf{F} = -e \mathbf{v} \times \mathbf{B}$

$$\mathbf{E} = -\mathbf{F}/e$$

Because of high plasma conductivity the E-field is not existent.

Axford1964 viscous interaction (of turbulent nature, KH/RT instabilities, KH instabilities at the flanks of the magnetosphere) is a viable source of drag force/solar storm energy input into magnetosphere

Otto&Nykyri1982 KH instabilities/vortices force magnetic reconnection even at northern IMF and are able to account for observed mass flux

Newell et al. (2007) and Newell et al. (2008): coupling consists of merging and viscous part (reconnection and turbulence)

merging part: universal sw-magnetosphere coupling function; rate magnetic flux is opened at the magnetopause ( $d\Phi_{\text{MP}}/dt$ )

viscous part: reconnection due to Kelvin-Helmholtz instabilities at the boundary ( $n^{1/2}v^2$ )

equation for the least variance linear prediction of  $K_p$ :  $K_p = 0.05 + 2.244 \times 10^{-4} d\Phi_{\text{MP}}/dt + 2.844 \times 10^{-6} n^{1/2} v^2$   
combination of both terms works best ( $r = 0.866$ )

Merkin2013 MHD simulation of velocity shear at magnetosphere boundary with northern IMF; KH instabilities; double-vortex sheet structure

The coupling between the solar wind and the magnetosphere is governed by reconnection and compression of the magnetic field lines.

## 2. Background knowledge

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the dayside reconnection is asymmetric  
half-wave rectifier coupling  
To describe this, coupling functions with different complexity were proposed (Newell, cites? and list).

The results were consistent with the well-known connection between geomagnetic disturbances and the southward component of the external (interplanetary) magnetic field (([Dungey 1961](#)); [Fairfield and Cahill Jr 1966](#)).

([Zhang & Burlaga 1988](#)): The magnitude of the change in the Dst index for the case when southward fields arrive first is comparable to that for the case when northward fields arrive first, and the phase is such that geomagnetic activity is associated with southward fields.

Southward interplanetary field can also occur in the shock sheaths ([Gonzalez and Tsurutani 1987](#); [Gosling and McComas 1987](#)), which have been shown to be equally important in causing geomagnetic storms ([Tsurutani et al. 1988](#)).

The results of this study indicate the equal importance of both sheath fields or draped fields and driver gas fields for the generation of major geomagnetic storms. Because of the importance of the sheath fields the intensity and duration of geomagnetic storms cannot be predicted by solar observations of active regions alone ([Tsurutani et al. 1988](#)).

Identification of a flux rope near the Sun makes it easier to predict the expected magnetic configuration at Earth, modified by the interaction with the solar wind on its way to Earth.

Bz prediction:  
read Savani2015: Predicting the magnetic vectors within coronal mass ejections arriving at Earth: 1. Initial architecture  
read Savani2015: Predicting the magnetic vectors within coronal mass ejections arriving at Earth: 2. Geomagnetic response

It makes sense to use the geocentric solar magnetospheric (GSM) coordinate system, which is aligned with the Earth's magnetic dipole axis.

dayside reconnection:  
“ $E_y$  is the rate at which southward magnetic flux is convected to the magnetosphere by the solar wind ( $-v_x \cdot B_z$ ) in GSM coordinates,” ([Russell 2007](#))

In this work I settle for  $vB_z$  as the coupling function – that is why I focus on this relation here.

The solar wind electric field  $E_y$  is the product of the proton velocity  $v$  and the magnetic field z-component  $B_z$ :

$$\text{?checkvectors} E_y = -v_x \times B_z . \quad (2.3)$$

annual Variation in Magnetic Disturbances  
The semiannual variation in geomagnetic activity has been recognized for a long period of time which shows the maximum appears around equinoxes while the minimum appears around solstices; by ([Cortie 1912](#))

A model, in which the interaction, ordered in solar magnetospheric (GSM) coordinates, is zero for northward components of the interplanetary field while the interaction is proportional to magnitude of the southward components predicts the correct phase and provides a yearly variation in the strength of the interaction sufficient to cause the observed effect. ([Russell & McPherron 1973](#))

This mechanism is the varying probability throughout the year of a southward component of the interplanetary magnetic field as seen by the magnetosphere. This arises from the changing orientation between the solar equatorial coordinate system (GSEQ), in which the interplanetary field is ordered, and the solar magnetospheric coordinate system (GSM), in which the interaction with the interplanetary field is ordered. ([Russell & McPherron 1973](#))

the R-M effect holds that the angle between Z axis in geocentric solar magnetospheric (GSM) coordinate system and Y axis in geocentric solar equatorial (GSEQ) coordinate system plays an important role. Figure 1a shows the semiannual and diurnal variation of the angle  $\theta$  between the Z axis in GSM coordinate system and

the Y axis in GSEQ coordinate system, that is, the controlling parameter of the R-M effect. According to the R-M effect, the probability of southward IMF increases when the angle  $q$ , which is smaller than 90 degrees, decreases, so that the dayside reconnection can be more efficient and more energy can be conveyed into the magnetosphere. (Zhao & Zong 2012)

whereas Russell et al. [2003] demonstrate that the tilt of dipole axis controls the size of dayside reconnection region and thus the reconnection rate and geomagnetic activity. Nowadays, the R-M effect is one of the most prevailing hypotheses. (Zhao & Zong 2012)

Thus, the R-M effect with positive/negative IMF polarity is more reasonable to explain seasonal and diurnal variation of geomagnetic activity under different IMF polarity and extreme solar wind conditions. (Zhao & Zong 2012)

causes (see citetRangarajan1997 p. 1282 and mention Bartels1963 too)  
read Bothmer1998 Ch 3...

Sonnerup & Cahill (1967): The rotational discontinuity seems to occur predominantly during magnetic storms and two of these cases, involving substantial normal-field components, provide compelling evidence that field reconnection takes place during the storm main phase.

## 2.6.4 Geomagnetic indices

Geomagnetic observatories are distributed widely over the globe, measuring the local magnetic field at their position. Several sets of stations, covering specific regions, are defined to monitor the state of different parts of the magnetospheric system. Magnetic measurements from these sets define several geomagnetic indices. The International Association of Geomagnetism and Aeronomy (IAGA) supports the following global geomagnetic indices which are serviced by the International Service of Geomagnetic Indices (ISGI)<sup>7</sup>: The  $aa$  index is designed to represent the amplitude of the global geomagnetic activity, normalized to a geomagnetic latitude of  $\pm 50^\circ$ . The  $am$  index characterizes the global geomagnetic activity. The  $K_p$  index is designed to measure geomagnetic disturbances from solar particle radiation – it is described in more detail in Section 3.3. The  $Dst$  index monitors the intensity of the magnetospheric ring current. The  $PC$  index monitors the polar cap magnetic activity – it approximates the amount of energy which entered the magnetosphere through solar-wind coupling. The  $AE$  index and its relatives  $AU$ ,  $AL$  and  $AO$  measure the magnetic effects of the northern auroral electrojet. The first three listed indices ( $aa$ ,  $am$  and  $K_p$ ) are calculated from different sets of local 3-hourly  $K$  indices, which measure the local magnetic disturbances at the observatories.

[for  $K_p$ ,  $AA$  and  $Dst$  read Section 7.4 in book Bothmer & Daglis (2007)...  
 $Dst$  (read book Jursa1985 p. 4-31)]

Lockwood et al. (2014) even used geomagnetic indices to reconstruct the near-Earth solar wind magnetic field strength and velocity back to 1845.

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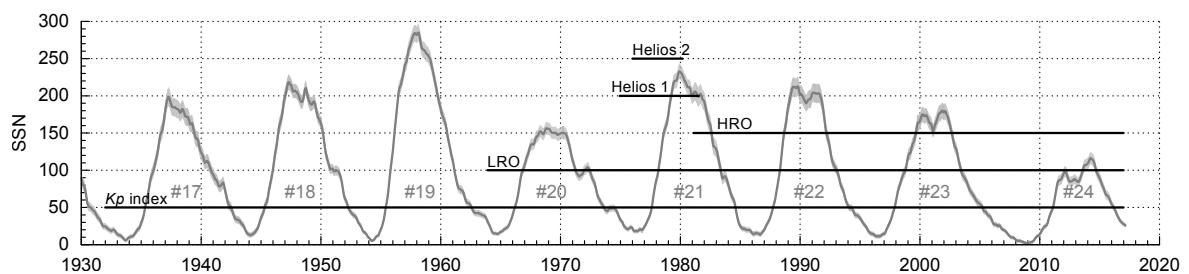
<sup>7</sup>ISGI website: <http://isgi.unistra.fr/>



### 3 Instrumentation and data description

For analyzing the solar wind and related areas on the Sun, there exist remote instruments (solar imagers and coronagraphs) and in-situ instruments (magnetometers and plasma detectors). In this chapter the basic principles of the latter are described, because the analyses performed in this thesis are based entirely on in-situ measurements – except of the sunspot time series.

Different kind of data, collected from observatories at various locations, are used for the investigations performed in this thesis. In the following sections, I describe the data sets of the magnetospheric disturbance index  $K_p$  and of the solar activity indicator sunspot number (SSN). Further, the solar-wind in-situ data sets are described: the near-Earth OMNI data collections consisting of minutely and hourly data, that is, low resolution OMNI (LRO) and high resolution OMNI (HRO), and the data obtained from the Helios 1 and Helios 2 space-craft in the 1970s. I plotted a time coverage overview of these data sets in relation to the solar activity cycles in [Figure 3.1](#).



**Figure 3.1** Time coverage of the data sets used in this work with the solar activity from 1930 until end of 2016. The individual data sets are the  $K_p$  index, the low and high resolution OMNI (LRO and HRO) collections, and the Helios 1 and Helios 2 data sets. I plotted the SIDC 13-month smoothed monthly SSN and the cycle number in the background for orientation.

#### 3.1 Magnetometer

Spacecraft nowadays carry two different magnetometer types, one for measuring the magnetic field direction and its strength and the other for observing the magnetic flux and detecting waves.

A flux-gate magnetometer consists of two coils around a core – one coil with alternating current, which is compared with the induced current signal from the other. Without external magnetic field both patterns match. The core is easier magnetized in direction of an existing external magnetic field, in which case the patterns differ. It measures...

In a search coil magnetometer one coil is placed around a core; measures plasma waves – where?

Because these magnetometer types are directional, they often are placed in two sets of triaxial configurations, attached on booms to minimize the influence of the spacecraft's own magnetic field.

L-> which is generated by surface charges?/electrons?/ionization?/the instruments?

figures and references...!

Ground based magnetometers measure the local magnetic field of the Earth. They already exist since...

examples:

ACE/MAG – flux-gate magnetometer

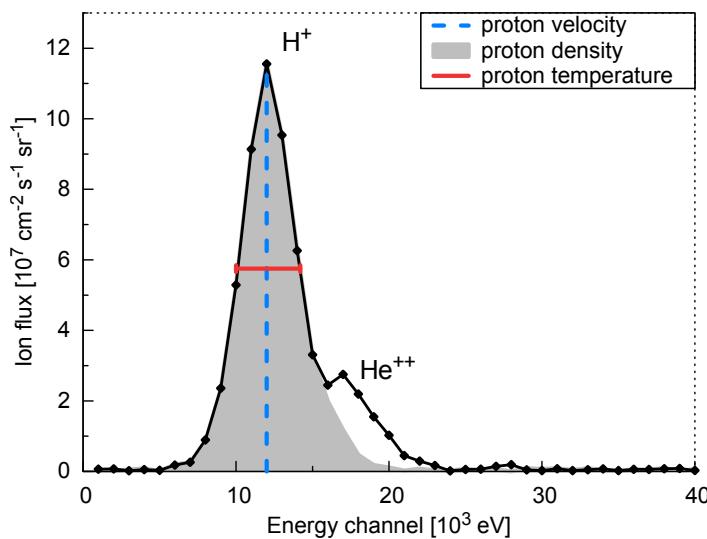
## 3.2 Plasma detector

several spectrometers with different energy ranges

- isotope spectrometer - isotopic abundances of SEPs
- ionic charge analyzer - charge state of SEPs
- solar wind ion mass spectrometer -
- solar wind ion composition spectrometer -
- radio burst tracker

A plasma detector measures the ion energy frequency distribution, which consists basically only of protons and alphas in solar wind. I prepared a synthetic ion energy spectrum for illustration in [Figure 3.2](#).

...read <http://www.goembel.biz/sun.html>



**Figure 3.2** Example of an ion energy spectrum for which I prepared some synthetic data points, including a small helium peak. Capitalize Proton...

The velocity, density, and temperature can be derived from the energy spectrum.  
more details...!

The bulk velocity is derived from the distribution's average energy (or position of Maxwell-Boltzmann distribution?).

The number density is the area of the distribution.

The temperature scales with the distribution's width.

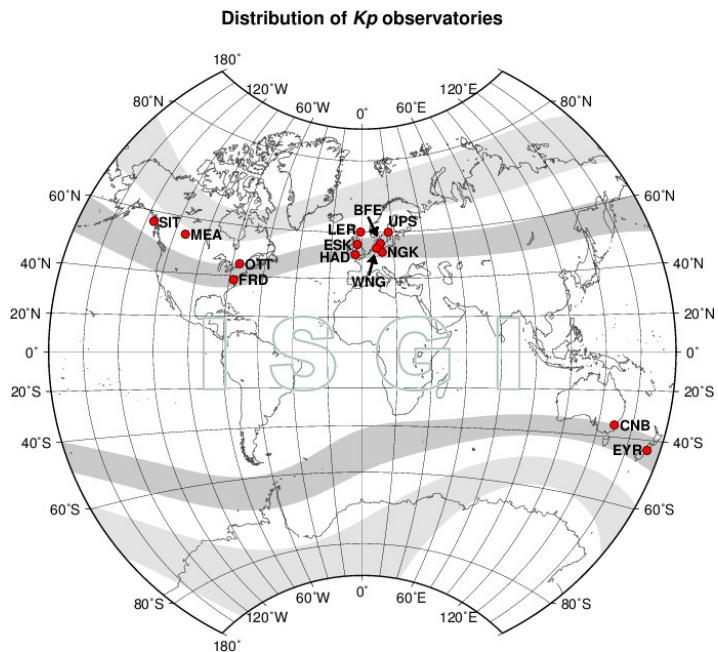
ACE/SWEPAM

## 3.3 K<sub>p</sub> index

Julius Bartels introduced the *K* index in 1938 and designed it to measure the intensity of geomagnetic disturbances ([Bartels et al. 1939](#)). Its name originates from 'Kennziffer' – the german word for characteristic digit. The *K* index is a measure for the maximal variation of the surface magnetic field, observed in a magnetogram within 3-hour intervals. Its scale in the range 0–9 is a quasi-logarithmic representation of the actual magnetic field strength's variations.

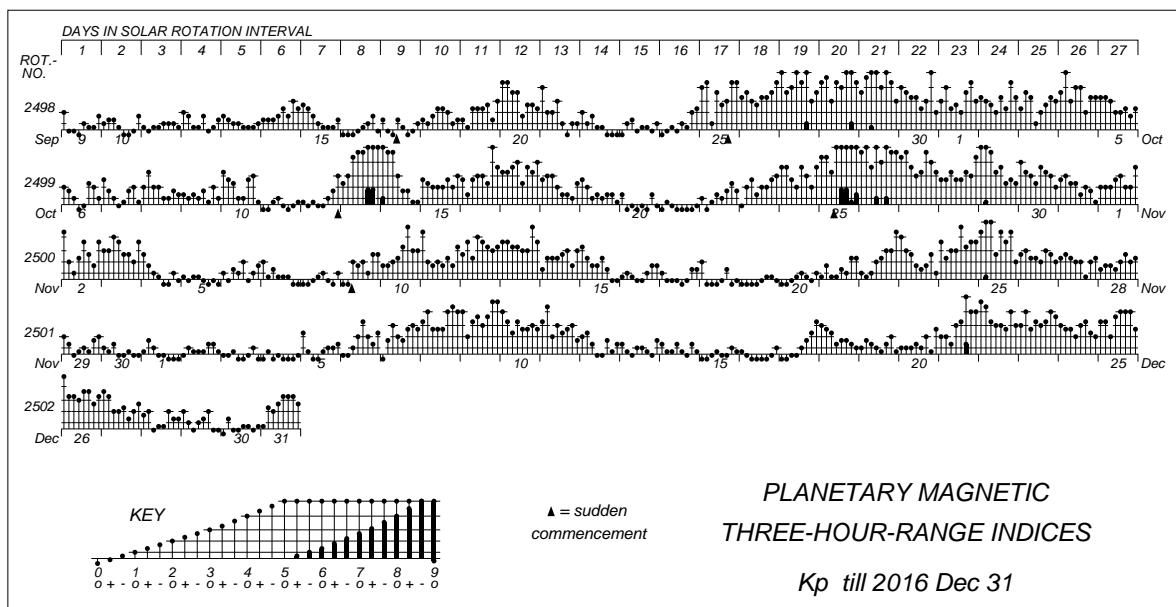
The Planetary *K* index (*K<sub>p</sub>*) is a planetary geomagnetic disturbance index, introduced by Bartels in 1949 at the Institute for Geophysics, University of Göttingen ([Bartels & Veldkamp 1949](#)). *K<sub>p</sub>* is the weighted average of 13 *K* indices, which are the standardized versions of the local *K* indices measured at 13 observatories. These contributing observatories are located around ±50° geomagnetic latitude and their distribution is biased towards Europe, see the map in [Figure 3.3](#).

To benefit from its higher precision, its scale, in the range 0–9 as well, is further divided into thirds, represented by the suffixes '+', 'o' and '-' (e.g., 3o, 3+, 4-, 4o). The *K<sub>p</sub>* indices are often visualized in musical



**Figure 3.3** Distribution of the 13  $K_p$  observatories. The shaded belts indicate regions of equal geomagnetic latitude. Courtesy of International Service of Geomagnetic Indices (ISGI), 2013.

diagrams, where they are stacked into periods of 27 days to enable the detection of recurrent activities, as seen in Figure 3.4.



**Figure 3.4** Bartels musical  $K_p$  diagram for the time period from September until end of December 2016. Two sudden commencements with following geomagnetic storms, having a maximal  $K_p$  of 6+, can be seen in October. Credit: GFZ Potsdam, 2017, licensed under CC BY 4.0.

The  $K_p$  index can be converted to the 3-hour equivalent  $ap$  index, which represents the magnetic field strength at a surface position of about 50° dipole latitude. The conversion is done via a table specified by Bartels, in which the value of the  $ap$  index is scaled in units of 2 nT, as seen in Table 3.1. There are further geomagnetic indices which are derived from the  $K_p$  index. They include  $Ap$ , the daily  $ap$  average,  $Cp$ , the daily  $ap$  sum mapped via a fixed table to the range 0–2.5, and  $C9$ , a mapping of  $Cp$  via a fixed table to the range 0–9. The definitions of Q-days (quiet days) and D-days (disturbed days) are also obtained from the  $K_p$  index.

The International Association of Geomagnetism and Aeronomy (IAGA) adopted the  $K_p$  index in 1954. The  $K_p$  index was maintained in Göttingen until January 1997 – now the German Research Centre for Geosciences (GFZ) in Potsdam supplies the  $K_p$  index and thereof derived indices. The GFZ provides historical

### 3. Instrumentation and data description

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**Table 3.1** Table for the fixed conversion from the  $K_p$  index to the equivalent  $ap$  index, which represents the magnetic field strength in units of 2 nT.

$K_p$	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
$ap$	0	2	3	4	5	6	7	9	12	15	18	22	27	32
$K_p$	5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
$ap$	39	48	56	67	80	94	111	132	154	179	207	236	300	400

and quicklook data of the indices via their website<sup>1</sup>. The data series was extended backwards using existing measurements and is now available from 1932 onwards.

There exist several indicators/quantities that scale or are based on the  $K_p$  index:

- NOAA's Space Weather Prediction Center (SWPC) developed its NOAA G-Scale<sup>2</sup> for geomagnetic storms which relates the  $K_p$  index to five levels from G 1 to G 5.
- The equatorward auroral boundary position correlates with the  $K_p$  index (cite?).
- The variation of the total electron content (TEC) of the ionosphere correlates with the  $K_p$  index (cite?). The TEC has influence on global navigation satellite systems (GNSS). A part of their positional error scales directly with TEC (in extreme cases up to about 30 m).

'The  $K_p$  index is designed to measure solar particle radiation by its magnetic effects.'

Because of the effects on sensitive technical systems, various methods for now- and forecasting the  $K_p$  index are developed:

- GFZ Potsdam Nowcast  $K_p$  index<sup>3</sup>.
- USAF Wing  $K_p$  model; 1–4 hours forecast from real-time solar-wind measurements<sup>4</sup>
- ?Alexej  $K_p$  correlation forecast model; developed within AFFECTS (link)
- In Chapter 4 of this work, I derive relations to enable  $K_p$  nowcast from in-situ solar-wind measurements and to enable  $K_p$  forecast from remote CME/solar-wind stream observations.

## 3.4 Sunspot number

The number of sunspots occurring on the solar surface is commonly used as a long-term solar activity indicator, for more information on solar activity and sunspots see Section 2.3. The international sunspot number (SSN) is maintained by the World Data Center – Sunspot Index and Long-term Solar Observations (WDC-SILSO) at the Solar Influences Data Center (SIDC), Royal Observatory of Belgium (ROB). The SIDC provides an online catalogue<sup>5</sup>, where I obtained the SSN data. The SSN version 2.0, the current recalibrated version introduced in July 2015, is used in this work. Chapter 4 uses the SSN data from the time period 1932–2016, see Figure 3.1.

Short-term predictions of the SSN are provided by several institutions. The SIDC itself provides 12-month SSN forecasts derived via different methods. The Space Weather Prediction Center (SWPC) at the National Oceanic and Atmospheric Administration (NOAA) supports the SSN prediction of the Solar Cycle 24 Prediction Panel<sup>6</sup>.

## 3.5 OMNI data collection

Solar wind was measured in situ for the first time by spacecraft in 1959 and since 1963 near-Earth measurements were done almost continuously. The OMNI 2 data collection (King & Papitashvili 2005) merges data from solar-wind magnetic field and plasma, energetic proton fluxes, geomagnetic indices, and solar indices. The included solar-wind data starts in 1963-11-27, the temperature data not before 1965-07-26, and is continuously maintained until today. As the data covers decades from multiple spacecraft at varying locations, the

<sup>1</sup>GFZ website for geomagnetic indices: <http://www.gfz-potsdam.de/en/kp-index/>

<sup>2</sup>NOAA Space Weather Scales website: <http://www.swpc.noaa.gov/noaa-scales-explanation>

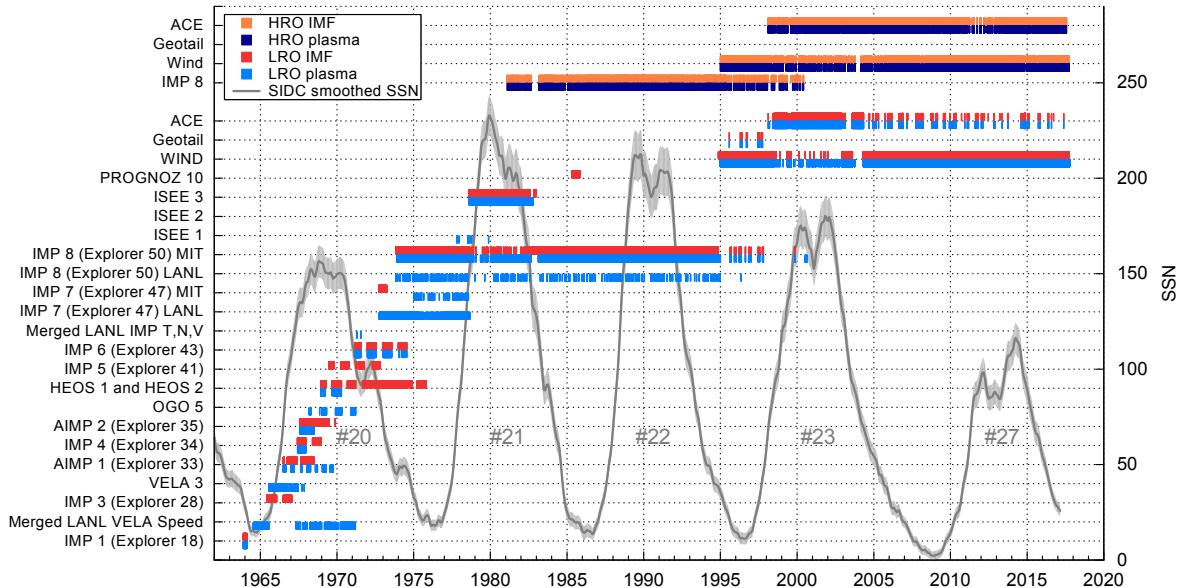
<sup>3</sup>GFZ Potsdam Nowcast  $K_p$  index website: [http://www-app3.gfz-potsdam.de/kp\\_index/ql\\_bar.gif](http://www-app3.gfz-potsdam.de/kp_index/ql_bar.gif)

<sup>4</sup>USAF Wing  $K_p$  model website: <https://www.swpc.noaa.gov/products/wing-kp>

<sup>5</sup>WDC-SILSO website: <http://www.sidc.be/silso/>

<sup>6</sup>Solar Cycle 24 Prediction Panel website: <http://www.swpc.noaa.gov/products/solar-cycle-progression>

solar-wind data is composed of intercalibrated data, which has been time-shifted to the nose of the magnetosphere's bow shock upstream of Earth. I created an overview of the various spacecraft contributing to the IMF and solar-wind plasma data and their time coverages to the data set in [Figure 3.5](#).



**Figure 3.5** IMF and solar-wind plasma data sources (spacecraft) for the high and the low resolution OMNI (HRO and LRO) data sets until the end of 2016. I plotted this figure using the spacecraft identifiers noted in the OMNIWeb Data Documentation<sup>7</sup>. The SIDC 13-month smoothed monthly SSN and the cycle number are plotted in the background.

The OMNI data set is being maintained at NASA's Space Physics Data Facility (SPDF), Goddard Space Flight Center (GSFC). Their OMNIWeb interface<sup>8</sup> and their Coordinated Data Analysis Web<sup>9</sup> (CDAWeb) provide the data – the latter is where I obtained it.

## 3.6 Helios probes

In order to observe solar wind in situ within the inner heliosphere, the nearly identical solar probes Helios 1 and Helios 2, one is pictured in [Figure 3.6](#), were launched in December 1974 and January 1976 respectively.

Until today, these both probes were the only spacecraft that measured solar wind in situ over large solar distance ranges with perihelia as close as 0.31 au and 0.29 au respectively. Their highly elliptical orbits in the ecliptic covered a solar distance range up to 0.98 au. Launched during solar cycle minimum, the data of both probes cover the rise to the maximum of solar cycle 21, that amounts to about 6.5 years of data at varying solar distances. I plotted the probes' solar distance and heliographic latitude with respect to their mission time and sunspot number for illustration in [Figure 3.7](#). The daily trajectory data are available from NASA's Space Physics Data Facility (SPDF) at the Goddard Space Flight Center (GSFC)<sup>11</sup> and are drawn in Heliographic Inertial (HGI) coordinates, see appendix [Section A.5](#). I also plotted the orbits of Helios 1 and Helios 2 in a solar equatorial plane view and in a solar polar plane view, see [Figure 3.8](#).

The scientific instruments carried by the spacecraft for measuring the magnetic field and solar-wind plasma are two different Flux-gate Magnetometers and the Plasma Experiment Investigation. The data from the magnetometer and plasma instruments are merged into a data set with hourly resolution ([Rosenbauer et al. 1977](#)). In case of Helios 1 this data set includes about 12.5 orbits in the time range 1974-12-10 to 1981-06-14 and in case of Helios 2 about 8 orbits in the time range 1976-01-01 to 1980-03-04. The Helios data is available via the GSFC/SPDF CDAWeb interface<sup>12</sup>.

The Helios 1 (Helios 2) magnetometer data coverage is about 43 % (54 %) and amounts to 2.8 years (2.3 years) in total. The plasma data coverage is 76 % (92 %) and amounts to 5.0 years (3.9 years) in total.

<sup>7</sup>OMNIWeb Data Documentation: [https://omniweb.gsfc.nasa.gov/html/ow\\_data.html](https://omniweb.gsfc.nasa.gov/html/ow_data.html)

<sup>8</sup>GSFC OMNIWeb interface: <http://omniweb.gsfc.nasa.gov/>

<sup>9</sup>GSFC CDAWeb interface: <http://cdaweb.gsfc.nasa.gov/>

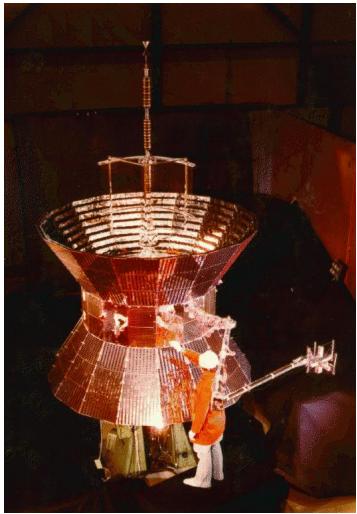
<sup>10</sup>I was not able to find out which Helios spacecraft this is.

<sup>11</sup>SPDF Helios 1 trajectory data: <http://spdf.sci.gsfc.nasa.gov/pub/data/helios/helios1/traj/>

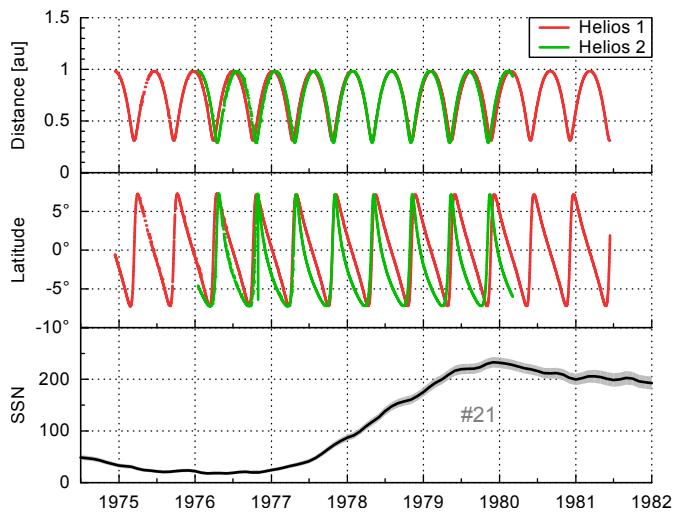
<sup>12</sup>GSFC CDAWeb interface: <http://cdaweb.gsfc.nasa.gov/>

### 3. Instrumentation and data description

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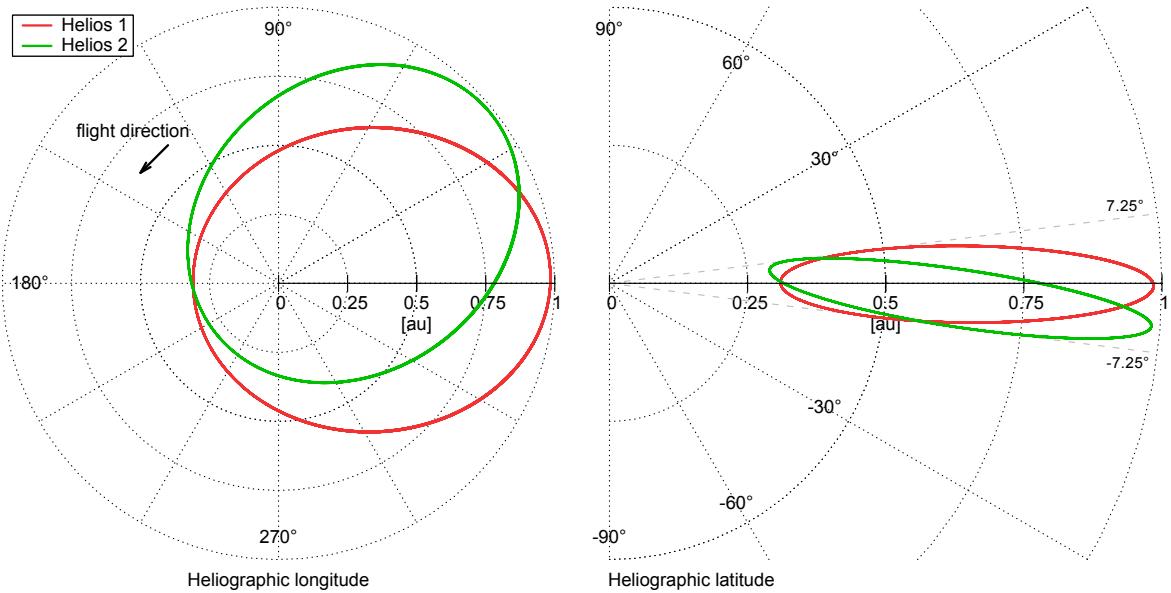


**Figure 3.6** One of the nearly identical twin Helios spacecraft<sup>10</sup>. Credit: NASA/Max Planck Institute for Solar System Research.

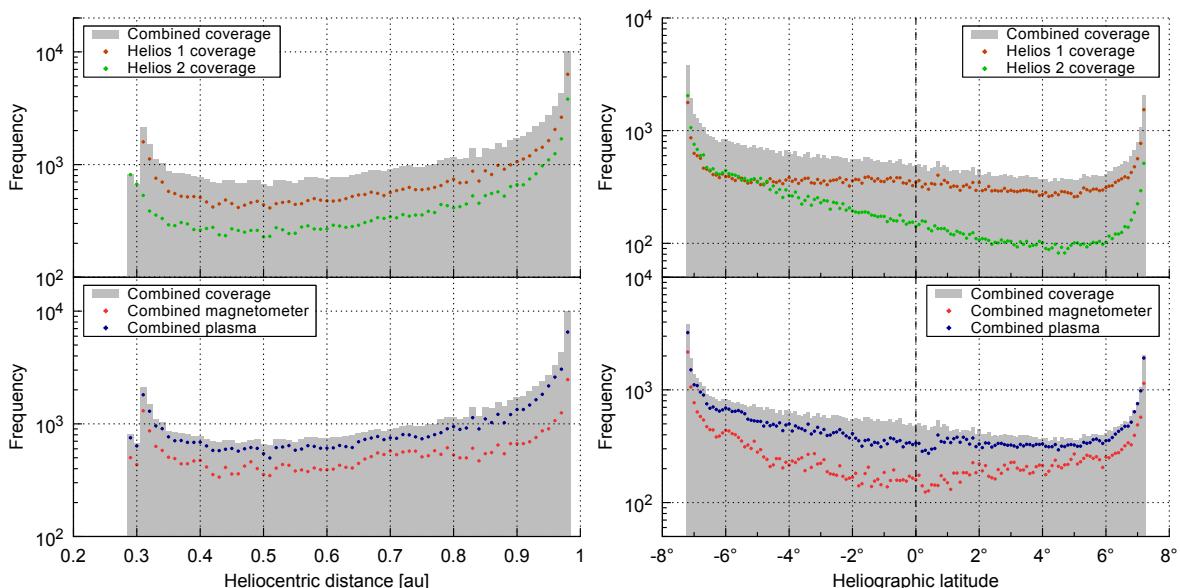


**Figure 3.7** Solar distance (top) and heliographic latitude (middle) of Helios 1 (red) and Helios 2 (green) with respect to their mission time. The trajectory data are from GSFC/SPDF and is plotted in HGI coordinates. I plotted the SIDC 13-month smoothed monthly SSN and its cycle number in the bottom panel for orientation.

The Helios magnetic field and plasma data frequency over heliocentric distance and over heliographic latitude are plotted in Figure 3.9.



**Figure 3.8** Orbit of the Helios 1 (red) and Helios 2 (green) spacecraft in the solar equatorial plane (left) and in the solar polar plane (right). I obtained the trajectory data from GSFC/SPDF and plotted the orbits in HGI coordinates.



**Figure 3.9** Helios data frequency over heliocentric distance with bins of 0.01 au (left panels) and over heliographic latitude with bins of 0.1° (right panels). The frequency data is based on the hourly merged magnetometer and plasma data sets for Helios 1 and Helios 2. The top panels show the frequencies for Helios 1 and Helios 2 individually and the bottom panels those for the magnetometer and plasma data.

### 3. Instrumentation and data description

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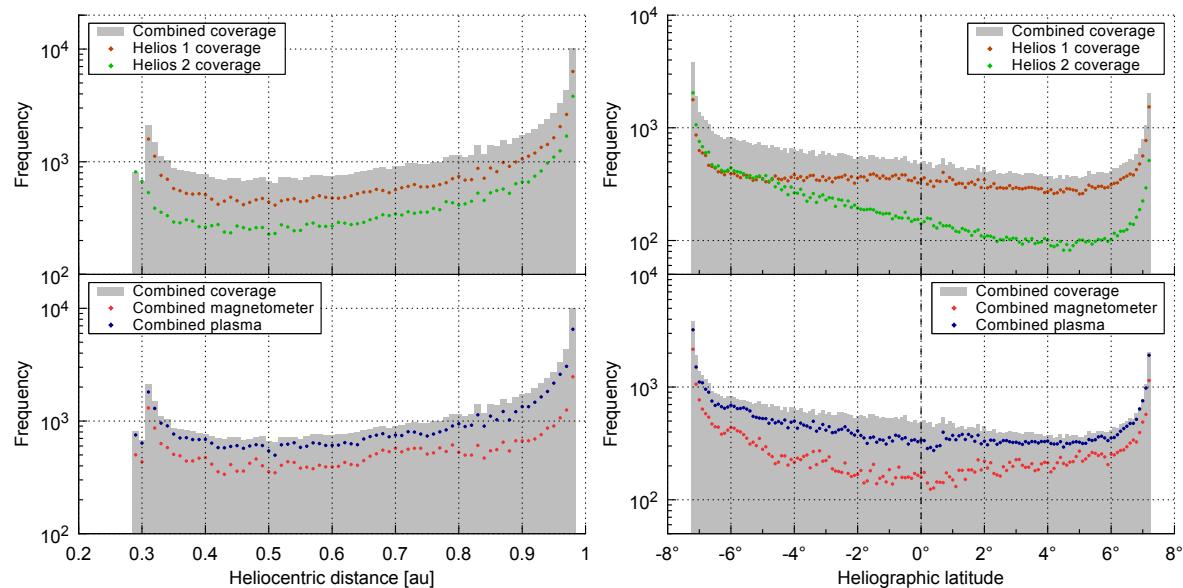


Figure 3.10

## 4 Solar wind and CME influence on the magnetosphere

Impact estimations derived from empirical correlations between in-situ solar-wind measurements and the geomagnetic  $K_p$  index

Variations in the Earth's magnetosphere are largely evoked by influence through the solar wind. These magnetospheric disturbances have diverse effects on the terrestrial environment. Especially the effects of severe geomagnetic storms created by coronal mass ejections (CMEs) pose various threats to sensitive technical systems and exposed humans. Thus, the development of quantitative forecasts for magnetospheric impacts caused by solar wind and CMEs is of major importance. The analyses in this chapter are based on my work done for the project Advanced Forecast For Ensuring Communications Through Space (AFFECS).

This study's goals are to estimate the magnetospheric impact from solar activity in general, from solar wind and also to predict it for CMEs in particular. Empirical dependencies between specific solar-wind parameters and the magnetospheric disturbance index  $K_p$  are presented. These dependencies allow to nowcast the  $K_p$  index from upstream (L1) solar-wind in-situ measurements. Hence, also the magnetospheric impact of CMEs is estimated solely based on their arrival velocities, predicted from coronagraph observations. The prediction of solar-wind stream velocities, e.g., from coronal hole observations, enables to estimate their impact as well.

First, I estimate the long-term variations of the yearly average  $K_p$  values, which are contributed by solar activity. This is achieved via logarithmic fitting of a yearly sunspot number (SSN) dependency. In order to nowcast the  $K_p$  index from general solar-wind conditions, I apply a correlation with the product of the parameters velocity and magnetic field z-component in GSM coordinates ( $vB_z$ ). In order to forecast the  $K_p$  index from estimated CME and stream velocities, I furthermore filter the solar-wind data, using flagged CME times from the solar-wind structures (SWS) list provided by Richardson & Cane (2012). The solar-wind data considered in these analyses consists of 35 years (1981–2016) of high-resolution minutely OMNI data, which is composed of multi-spacecraft intercalibrated in-situ measurements from 1 au. I evaluate various data processing methods and choose the methods resulting in the highest correlation coefficients with  $K_p$ . I analyze the  $K_p$  frequency distributions with respect to the depending parameters  $vB_z$  and velocity, derive their mean  $K_p$  per interval and further compile functional dependencies via logarithmic fitting.

The obtained functional relations enable to empirically estimate the mean  $K_p$  impact from measured solar activity, in-situ solar wind, and remotely determined CME and stream velocities.

### 4.1 Introduction

It is known since the early 19th century that variations in the solar wind evoke disturbances in the magnetosphere (Bartels 1962). Especially strong disturbances, called geomagnetic storms, can be provoked by coronal mass ejections (CMEs), which are embedded within the solar wind. The causes of the strongest geomagnetic storms are the compression of the solar-wind magnetic field lines within the CME shock front and the enhanced field strengths of magnetic clouds, which are enclosed in CMEs (Bothmer 1993). The consequences of strong geomagnetic disturbances are a threat to sensitive technical systems and exposed humans. Therefore it is important to know when magnetospheric disturbances will occur and how large they will become.

$K_p$  is designed for... (cite?). I use this magnetospheric disturbance index to correlate it with near-Earth solar-wind measurements. More detailed information on the  $K_p$  index can be found in Section 3.3.

current comparable  $K_p$  forecast models take into account...  
Elliott et al. (2013): The  $K_p$  index and solar-wind speed relationship: Insights for improving space weather forecasts  
differences to existing studies:  
here I show...

With the results presented in this chapter, I elaborate the step from the predicted CME and stream velocities to the forecast of the possible impact strength on the terrestrial magnetosphere. I derive an empirical correlation between the solar-wind speed and the geomagnetic  $K_p$  index, in order to obtain the capability to forecast  $K_p$

## 4. Solar wind and CME influence on the magnetosphere

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values solely based on the predicted CME and stream velocities. The derived functional dependencies can be used to nowcast/forecast the  $K_p$  index.

In-situ measurements of solar wind are made almost continuously, e.g., at the first Lagrange point (L1), in front of the magnetosphere. Since 1963 several spacecraft collected more than 50 years of solar-wind data. The latest spacecraft, e.g., Wind, ACE and DSCOVR (launched in early 2015), provide real-time solar-wind data online<sup>1 2 3</sup>. These solar-wind real-time data are used to nowcast various effects on the Earth's magnetosphere, such as the position of the magnetospheric bow shock in front of the Earth, the magnitude of geomagnetic disturbances (e.g.,  $K_p$  index), the positions of the polar auroral ovals, the variation of the total electron content (TEC) of the ionosphere, and the positional error of global navigation satellite systems (GNSS).

The velocity and the direction of CMEs can be determined in their early near-Sun stages via remote tracking with coronagraph white-light observations. Using these parameters as input for CME propagation models, their possible arrival time and arrival velocity at Earth can be derived.

read Savani2015: Predicting the magnetic vectors within coronal mass ejections arriving at Earth: 1. Initial architecture

read Savani2015: Predicting the magnetic vectors within coronal mass ejections arriving at Earth: 2. Geomagnetic response

Coronal holes are the origin of the fast solar wind; their area on the solar disk, seen in EUV wavelengths, correlates with the measured velocity of solar-wind streams (Vršnak et al. 2007). This relation is used to predict the Earth-arrival velocity of solar-wind streams about 4 days in advance (Rotter et al. 2012), as is done in real-time within the empirical solar-wind forecast (ESWF) at the University of Graz<sup>4</sup>.

mention ENLIL forecast simulation

For the analyses performed and found in this chapter, the objectives are to estimate the magnetospheric impact of solar wind and to predict it for CMEs in particular. In Sect. 4.2 I determine the magnitudes of the long-term  $K_p$  changes due to solar activity and measure the extent of seasonal variations stemming from the Earth's orbit. In order to nowcast the  $K_p$  index, I quantify the solar-wind influence on  $K_p$  by deriving a functional relation with the product of solar-wind velocity and magnetic field z-component (Sect. 4.4). Finally, for the purpose of enabling  $K_p$  forecasts from remote observations, I estimate the  $K_p$  impact coming from CMEs and solar-wind streamers separately by deriving functional dependencies with their velocities (Sect. 4.5).

## 4.2 Long-term variations of the $K_p$ index

### 4.2.1 Solar activity influence

The  $K_p$  data is obtained from the GFZ Potsdam<sup>5</sup>, where the index is currently maintained. The data used in this analysis covers the time period 1932–2016. Its frequency distribution shows that the highest frequencies occur around low  $K_p$  values of 1+. Going to higher  $K_p$  values, the frequencies seem to decline asymptotically towards zero (see Fig. 4.1) – a  $K_p$  value of 90 occurred only 29 times in this time interval.

Obviously the general  $K_p$  distribution (seen in Fig. 4.1) averages over solar activity. Solar activity is generally tracked with the international sunspot number (SSN). In the present analyses its data from the time period 1917–2016 is used. The data is obtained from the online catalog<sup>6</sup> provided by the World Data Center – Sunspot Index and Long-term Solar Observations (WDC-SILSO), Solar Influences Data Analysis Center (SIDC), Royal Observatory of Belgium (ROB).

The  $K_p$  frequency distributions' shape varies with different states of solar activity. This is visible in the yearly distributions, sorted and colored by yearly SSN in Fig. 4.2.

<sup>1</sup>Wind real-time data website: <https://pwg.gsfc.nasa.gov/windnrt/>

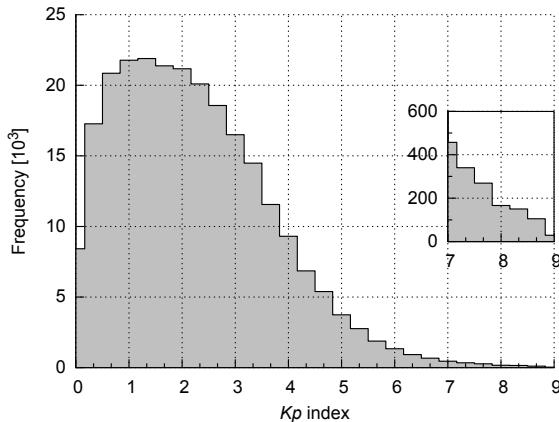
<sup>2</sup>ACE real-time data website: <http://www.swpc.noaa.gov/products/ace-real-time-solar-wind>

<sup>3</sup>DSCOVR real-time data website: <http://www.swpc.noaa.gov/products/real-time-solar-wind>

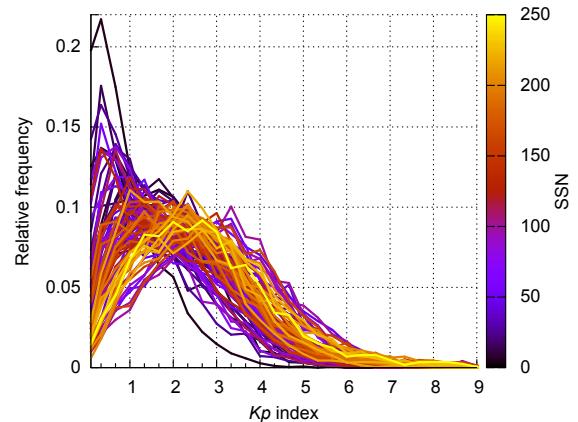
<sup>4</sup>ESWF website: <http://swe.uni-graz.at/index.php/services/solar-wind-forecast>

<sup>5</sup>GFZ Potsdam website: <http://www.gfz-potsdam.de/de/kp-index/>

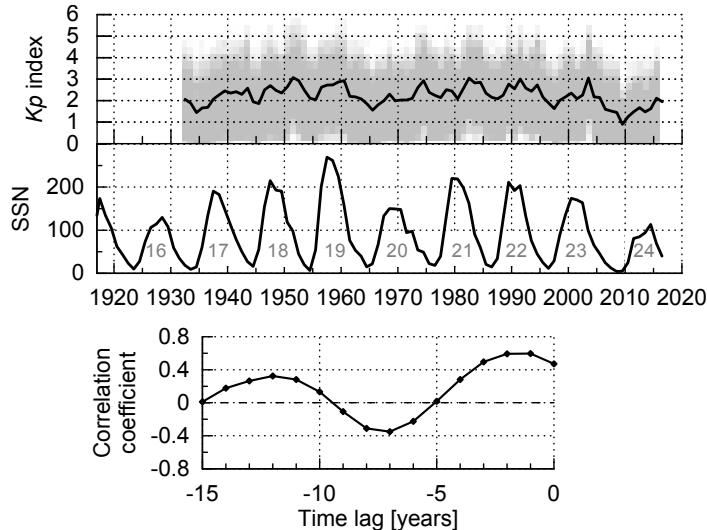
<sup>6</sup>WDC-SIDC website: <http://www.sidc.be/silso/>



**Figure 4.1**  $K_p$  frequency distribution for the time period 1932–2016. The inset shows a zoomed-in view of the high-value tail. The  $K_p$  data is obtained from the GFZ Potsdam.



**Figure 4.2** Yearly  $K_p$  frequency distributions during the period 1932–2016, sorted and colored by yearly SSN. All distributions are normed to be of equal area. The  $K_p$  data is obtained from the GFZ Potsdam and the yearly SSN data from the SILSO World Data Center.



The distribution's peak position scales with SSN, that is, a high yearly SSN results in a higher abundance of large  $K_p$  values as well.

The time series of yearly average  $K_p$  values of the years 1932–2016 shows an imprint of the solar cycles (see the top graphs in Fig. 4.3). The  $K_p$  pattern follows the solar cycle minima and maxima as well as the changes in magnitude between solar cycles. The yearly mean  $K_p$  shifts about 1 unit for both variations separately. As expected, the  $K_p$  index correlation with solar activity shows an 11-year period (see bottom graph in Fig. 4.3). The highest correlation coefficient of 0.60 is found with a time lag of –1 year, that is, the yearly average  $K_p$  follows the SSN of the previous year.

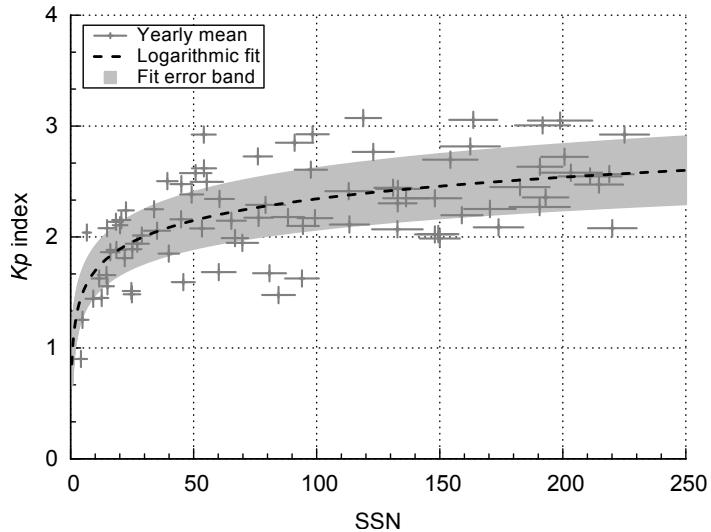
The yearly mean  $K_p$  index with respect to the 1-year lagged SSN shows a raise with increasing SSN, this is seen in Fig. 4.4. I perform a fit in order to obtain an analytical relation for this dependency.  $K_p$  itself is a quasi-logarithmic index, so it is apparent to use a logarithmic fit function:

$$f(x) = a \cdot \ln(x) + b. \quad (4.1)$$

The fit parameters are  $a = 0.281(43)$  and  $b = 1.05(19)$  and lead to the relation

$$K_p(ssn) = 0.28 \cdot \ln(ssn) + 1.1, \quad (4.2)$$

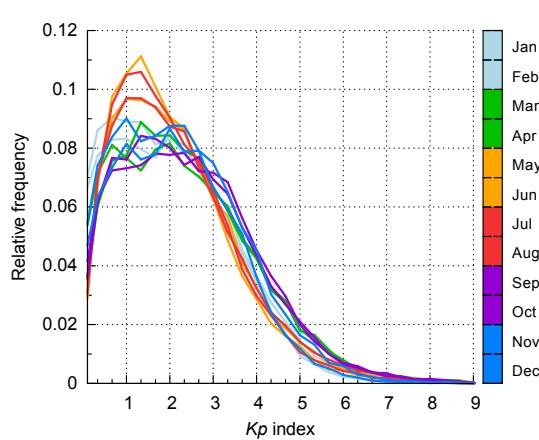
which is plotted in Fig. 4.4. This means that for a SSN of 1 the mean  $K_p$  is about 1.1 and for a SSN of 200 it is about 2.5. The fit error band has a width of about half a  $K_p$  unit.



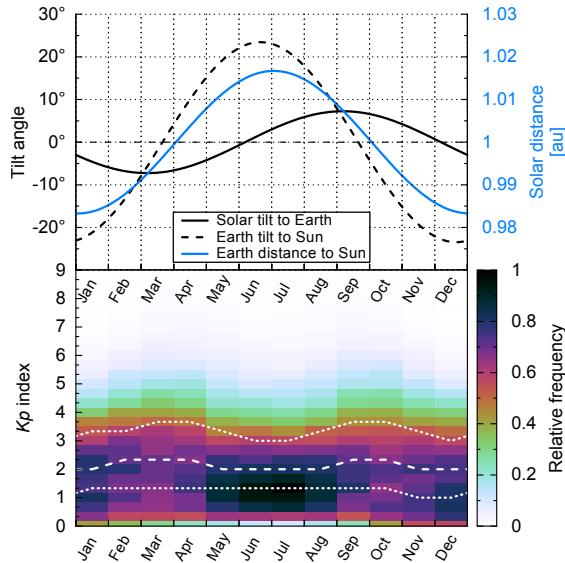
**Figure 4.4** Yearly mean  $K_p$  index with respect to 1-year lagged SSN (+) with the weighted logarithmic fit (dashed). The error bars denote the SSN standard deviation and the relative weight from the yearly data coverage. The shaded area represents the fit error band derived from the estimated standard deviations of the fit parameters. The logarithmic function, equation (4.1), is used for the weighted fit. The yearly  $K_p$  mean values are calculated from GFZ Potsdam data and the yearly SSN is obtained from the SILSO World Data Center.

## 4.2.2 Seasonal variations

On top of the yearly variations, seasonal variations exist in the magnetospheric disturbances as well. In the months May–August the  $K_p$  peak frequency is higher than in the remaining months of the year, whereas in March/April and September/October the  $K_p$  values  $>3$  are more abundant. This is apparent from looking at the monthly  $K_p$  frequency distributions, plotted in Fig. 4.5. These  $K_p$  changes arise from seasonal variations of the



**Figure 4.5** Average monthly  $K_p$  frequency distributions of the time period 1932–2016, colored by month of the year. The  $K_p$  data is obtained from the GFZ Potsdam.



**Figure 4.6** Seasonal changes in the solar tilt angle to Earth, Earth tilt angle to Sun, and Earth distance to Sun – the curves are approximated with trigonometric functions (top).  $K_p$  frequency distributions by month for the time period 1932–2016 with median and quartile values (bottom). The bin size is 1 month and  $1/3 K_p$  unit respectively.

solar-wind parameters at Earth, which stem from Earth’s yearly changes in orbital distance and heliographic latitude. Another seasonal effect stems from the Earth’s rotation axis tilt, which changes the direction of the Earth’s magnetic dipole axis to the Sun over the year (see top panel of Fig. 4.6).

Earth’s distance to the Sun varies over the course of a year by  $\pm 1.67\%$  (see appendix Section A.4). The solar-wind parameters scale via power-law dependencies with solar distance, as is described in the following Chapter 5 and accordingly in Venzmer & Bothmer (2017). For example, if the solar-wind proton density scales with  $r^{-2}$ , this leads to yearly variations in density of up to 3.4 %. These yearly solar-wind changes have a direct influence on the  $K_p$  index.

The Sun's rotation axis tilt angle to the ecliptic is  $\pm 7.25^\circ$  and that for Earth is  $\pm 23.44^\circ$  (cite 'NASA Earth fact sheet' or U.S. Nautical Almanac Office 2015), see also appendix [Section A.4](#). The solar-wind magnetic field strength varies with heliographic latitude (cite?). Furthermore, the rate of magnetic reconnection between solar wind and the Earth's magnetosphere depends on both fields' orientation to each other (parallel/antiparallel) (see also Basics, Figure XX). The solar-wind influence on the  $K_p$  index depends on its coupling efficiency with the magnetosphere. Additionally, the tilt of the magnetic dipole axis to the rotation axis – a few degrees for the Sun during cycle minima (extreme during solar maximum...) and about  $10^\circ$  for the Earth – complicates this system even more.

So the  $K_p$  variation effects originate from the seasonal changing of the solar tilt, the Earth's tilt, and the Earth's distance. Thorough analyses of the seasonal variations were already performed by ([Cortie 1912](#)) (more cites?). Thus, I just quantify the bulk magnitude of these effects (and include them as relative uncertainties). Looking at the  $K_p$  frequency distributions by month – seen in the bottom panel of Fig. 4.6 – it is apparent that for high  $K_p$  values ( $> 4$ ), there exist yearly frequency maxima at the equinoxes and frequency minima at the solstices, which was described by ([Cortie 1912](#)). It can be seen that this semiannual variation amounts to about 1  $K_p$  unit.

The changes from the  $K_p$ -SSN relation (4.2) and the seasonal variations are of similar order (about 1  $K_p$  unit).

## 4.3 Solar wind-magnetosphere coupling function

The coupling between the solar wind and the magnetosphere is governed by reconnection and compression of the magnetic field lines (see [Subsection 2.6.3](#)).

In this work I settle for ([Equation 2.3](#)),  $vB_z$  as the coupling function.

The solar wind electric field  $E_y$  is the product of the proton velocity  $v$  and the magnetic field z-component  $B_z$ :

$$\text{?checkvectors} E_y = -v_x \times B_z. \quad (4.3)$$

If not specified otherwise,  $B_z$  is always meant to be in GSM coordinates hereafter.

The solar wind velocity sticks mostly to its radial flow direction, that is, it only rarely deviates up to  $0.0^\circ$  (correct and cite...). Thus, the absolute flow speed can be used instead of the vector component.

- argue for  $vB_z$ :
- 3hmin( $vB_z$ ) performs in rank correlation slightly better than the sophisticated Newell formula. really?
- simple to calculate
- ...

It is also known that the solar-wind velocity itself already correlates strongly with the  $K_p$  index. In fact, [Machol et al. \(2013\)](#) even proposed a linear function of the  $K_p$  index as a best proxy for corrupted real-time velocity measurements made by the Advanced Composition Explorer (ACE) spacecraft.

I use this velocity relationship for obtaining  $K_p$  proxies from CME and solar wind stream data.

## 4.4 $K_p$ nowcast from in-situ solar-wind measurements

### 4.4.1 Data correlation

The  $K_p$  time series started in 1932 when there existed no spacecraft to measure solar wind in situ. Thus, the surveyed time range is defined by the available in-situ solar-wind data.

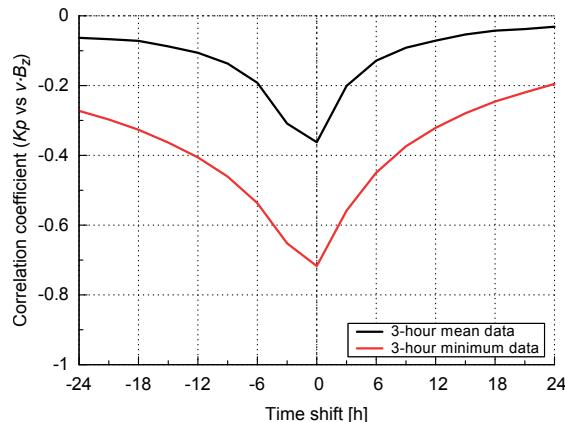
The  $K_p$  index represents maximal variations within 3-hour time intervals (see [Section 3.3](#)). Any solar-wind parameter that will be correlated with  $K_p$  also has to have the same time resolution. In addition to adapting the time resolution, it has to be considered by which means this should be done. Simple 3-hour average values are expected to have a lower correlation coefficient than the solar-wind parameter's 3-hourly maximal variation.

The 3-hour maximal variations are obviously higher when using high resolution data. Thus, to be able to correlate  $K_p$  with solar-wind data, high resolution data (e.g., 1 min) is needed to determine the maximal solar-wind variations within each 3-hour interval.

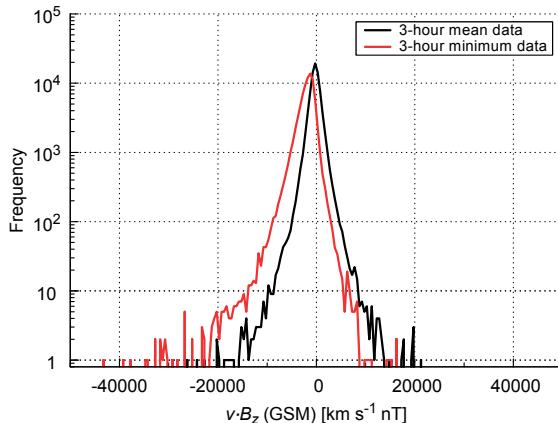
The OMNI data set collects the longest continuous solar-wind measurements at 1 au. The longest time coverage has the hourly OMNI data set (since 1963), however, I prefer to use the minutely OMNI data with the time range 1981–2016. [to benefit from higher correlation coefficients (see Figs?).]

why this data set? - because of long time coverage, to magnetospheric bow shock calculated solar wind and integrated geomagnetic indices (see Paper...)

The  $K_p-vB_z$  Pearson correlation coefficients for 3-hour mean and minimum data are plotted in Fig. 4.7. The largest correlation is found for the 3-hour minimum data without time shift. It is a negative correlation



**Figure 4.7**  $K_p-vB_z$  correlation coefficients for different time shifts up to  $\pm 24$  hours. Minutely OMNI data from 1981–2016 processed with mean (black) and minimum (red) 3-hour averaging.



**Figure 4.8** Frequency distributions of  $vB_z$  for 3-hour mean (black) and minimum (red) minutely OMNI data from 1981–2016.

with a coefficient of  $-0.72$ . For  $vB_z$  3-hour minimum values, their frequency distribution and its peak is asymmetrically shifted to negative values, as seen in Fig. 4.8.

### 4.4.2 Functional dependency for solar wind

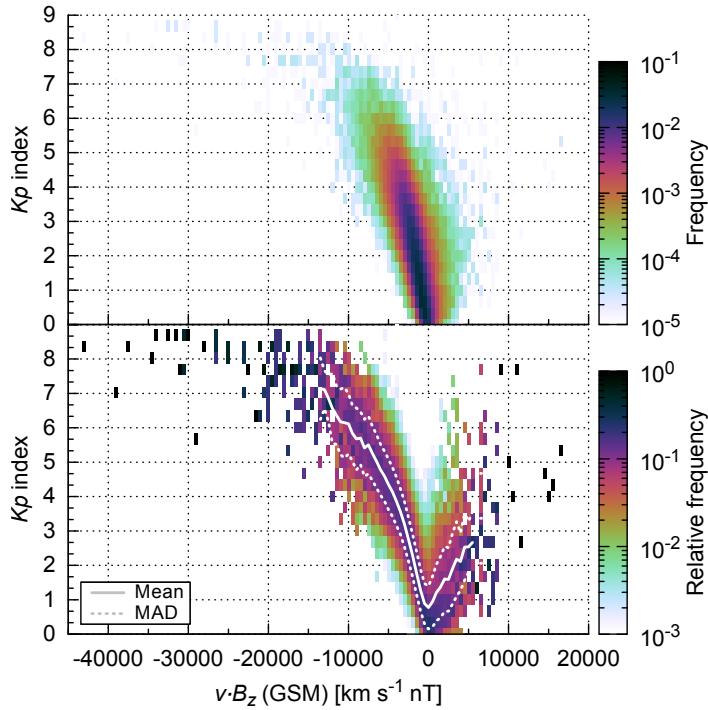
The frequency distribution in  $K_p-vB_z$  space is shaped like a candle flame, inclined to negative values by a light breeze, see top panel in Fig. 4.9. In order to determine a functional dependency, I focus on the relative frequencies per  $vB_z$ -interval and their mean  $K_p$  values, which are plotted in the bottom panel of Fig. 4.9. The mean absolute deviation (MAD) of the mean has a mean size of  $0.7 K_p$  units. This probability distribution is asymmetrically V-shaped around zero, having a larger and steeper negative arm than positive arm. The asymmetry also exists for 3-hour mean data, thus this effect is not a result of the data reducing method (3-hour minimum) (fig...?). Rather the steeper negative arm is a consequence of the half-wave rectifier coupling of the solar-wind magnetic field direction to the magnetosphere, as described in Subsection 2.6.3.

Since the  $K_p$  index has a quasi-logarithmic scaling (see Section 3.3), a logarithmic function is the obvious choice as a fit function. Furthermore, the depending argument consists of a product of two solar-wind parameters which individually scale logarithmically with  $K_p$ . These reasons are why I use the logarithm of a parabola for the fitting approach:

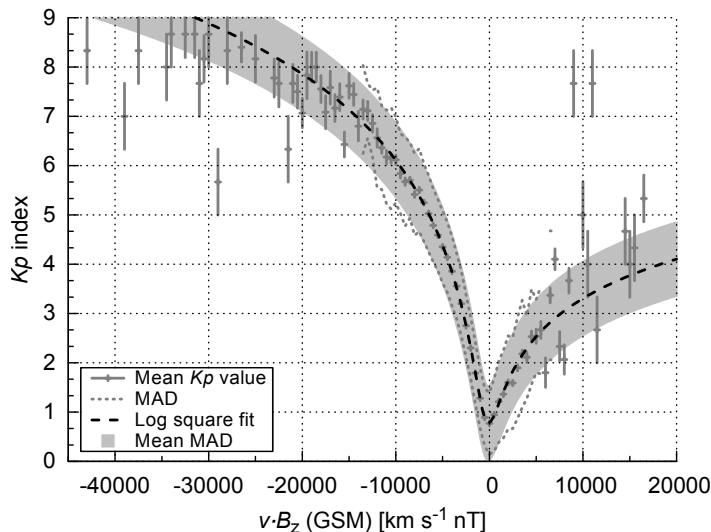
$$f(x) = \ln(x^2). \quad (4.4)$$

I also introduce a horizontal shifting parameter  $x'$  because the distribution's center is slightly offset. To be able to replicate the asymmetry in both arms, I further split the fit function into a negative and a positive part:

$$f(x) = \begin{cases} f_-(x) & \text{for } x < 0, \\ f_+(x) & \text{for } x \geq 0. \end{cases} \quad (4.5)$$



**Figure 4.9**  $K_p$  versus  $vB_z$  frequency distribution (top) and its relative distribution (bottom) with the mean  $K_p$  values (solid) and their mean absolute deviation (dotted). It is 3-hour minimum data from the minutely OMNI data set (1981–2016). The bin size is  $500 \text{ km s}^{-1} \text{ nT}$  and  $1/3 K_p$  unit respectively.



**Figure 4.10** Mean  $K_p$  values (+) and MAD values (dotted) per  $vB_z$  interval. The error bars represent the relative data count. The logarithmic fit (dashed) is plotted with a mean MAD band (shaded area). The splitted function (4.5) is used for the weighted fit.

This way, both arms can be scaled individually with the scaling factors for the negative and positive parts  $a_-$  and  $a_+$ . The resulting logarithmic fit functions are

$$f_-(x) = a_- \cdot \ln((x + x')^2 + b) + y', \quad (4.6)$$

$$f_+(x) = a_+ \cdot (f_-(x) - f_-(-x')) + f_-(-x'), \quad (4.7)$$

with the vertical shifting parameter  $y'$  and the depth parameter  $b$ . The resulting fit curve is plotted in Fig. 4.10 with the fit coefficients  $a_- = 1.258(19)$ ,  $y' = -17.04(33)$ ,  $a_+ = 0.467(20)$ ,  $b = 1.416(68) \times 10^6$ , and  $x' = 163(20)$  for units of  $[\text{km s}^{-1} \text{ nT}]$ . The mean MAD is about  $0.7 K_p$  units. Thus, the solar-wind dependency relation condenses to:

$$Kp_-(vB_z) = 1.258 \cdot \ln((vB_z + 163)^2 + 1.416 \times 10^6) - 17.04, \quad (4.8)$$

$$Kp_+(vB_z) = 0.467 \cdot (Kp_-(vB_z) - Kp_-(-163)) + Kp_-(-163). \quad (4.9)$$

This relation can be used together with real-time in-situ measurements from spacecraft located at L1 (see Section XX rt sources) to nowcast the actual  $K_p$  index.

## 4.5 **K<sub>p</sub> forecast from remote CME and stream observations**

CMEs are already sighted raising from their source regions on the solar surface. Some CME properties can be estimated from remote coronagraph observations and modeled to Earth, such as its propagation direction, its arrival time, and arrival velocity (cites?). Thus, early observations enable a heads-up time only depending on the CME's propagation speed to Earth. This travel duration can be more than 4 days for slow events with average solar-wind speeds, about 40 hours for fast events with speeds of  $1000 \text{ km s}^{-1}$ , and down to 20 hours and even below for the rare extreme cases, e.g., about 21 hours for the event on 23 July 2012 (Russell et al. 2013; Temmer & Nitta 2015) and about 19 hours for the event observed by Carrington (1859) on 1 September 1859.

To make use of the heads-up time for CMEs, I neglect its magnetic field part, which can hardly be determined from remote observations and simplify the coupling relation (2.3) from before. Therefore, the only coupling parameter remaining is the solar-wind velocity.

### 4.5.1 CME velocity estimation

methods and modeling...?

GCS, CAD modeling -> propagation direction and apex height-time profile -> acceleration and velocity kinematics...

-> example event CME?

### 4.5.2 Solar wind stream velocity estimation

CH analysis (Graz)

L4 shift (Graz)

WSA-ENLIL MHD simulation

### 4.5.3 Solar Wind Structures list

For the following analysis, I use the list of solar-wind structures (SWS) created and updated by Richardson et al. (2000) and Richardson & Cane (2012), who characterized the near-Earth solar-wind structures since 1963. All periods related to ICMEs in the OMNI solar-wind data set were identified and flagged.

list identifying criteria...

The SWS list for 1963–2016 was kindly provided by Ian Richardson (private communication). into acknowledgments...

SWS list for 1963–2015 by (Richardson et al. 2000; Richardson & Cane 2012) is available via registration at CEDARweb<sup>7</sup>.

List of near-Earth ICMEs since January 1996 by Cane & Richardson (2003); Richardson & Cane (2010). Available as ACE Level 3 data for the period 1995–mid2016<sup>8</sup>.

The CME fraction in the OMNI data is 15.8 % during the time period 1981–2016 (this accumulates to 5.53 years). This percentage is an average value. It varies heavily with the solar activity cycle and with the appearance of individual active regions on the solar surface. In the following, I refer to the remaining part without CMEs as “solar-wind streams”, because it is composed entirely from a mixture of slow wind flows, fast wind streams, and their interaction regions.

Solar Wind Structures (SWS) list

derived by Richardson.... from OMNI data (only?) permission received.

characterization of near-Earth solar-wind structures since 1963

SWS lists (Richardson et al. 2000) and (Richardson & Cane 2012)

<sup>7</sup>CEDARweb website for Solar Wind Structures: [http://cedarweb.vsp.ucar.edu/wiki/index.php/Tools\\_and\\_Models:Solar\\_Wind\\_Structures](http://cedarweb.vsp.ucar.edu/wiki/index.php/Tools_and_Models:Solar_Wind_Structures) (existent in 2017-10-29)

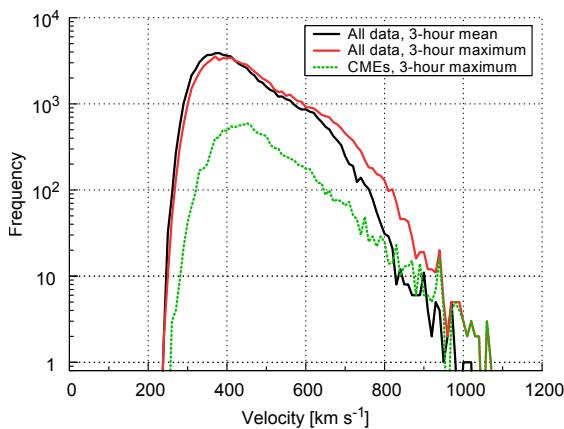
<sup>8</sup>ACE Level 3 data website – list of near-Earth ICMEs: <http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm> (existent in 2017-10-29)

**Table 4.1** Time lags with the highest correlation coefficients for the  $Kp$ -velocity relation for the whole OMNI data, for stream data, and for CME data. The values are based on the 3-hour maximum of the minutely high resolution OMNI data from the time period 1981–2016.

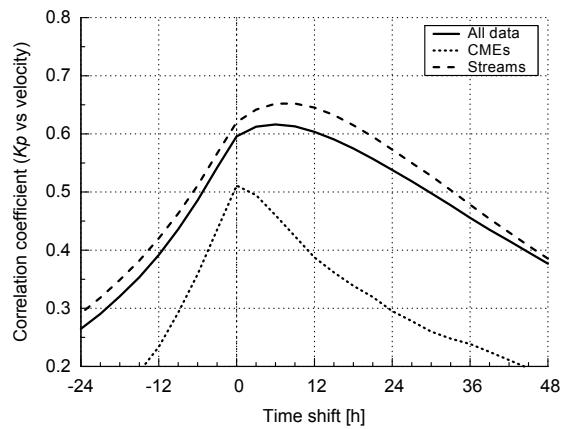
Data	Time lag [hours]	Correlation coefficient
All data	6	0.622
Streams	9	0.661
CMEs	0	0.511

#### 4.5.4 Data correlation

Again, I calculate 3-hour extreme values using the minutely OMNI data to profit from higher correlation coefficients, as done before for the data processing of the  $vB_z$  analysis in Sect. 4.4.1. The velocity has only positive values, thus its extreme values are 3-hour maximum values. The comparison between the 3-hour maximum and the 3-hour mean frequency distributions shows that their mean position shifts from a velocity of 405 to 425 km s $^{-1}$ , see Fig. 4.11. The CME part and solar-wind stream part of the data can be examined separately,



**Figure 4.11** Solar-wind velocity frequency distributions for 3-hour mean (black), maximum (red) and maximum of the CME part (green). Minutely OMNI data from the period 1981–2016 is used.



**Figure 4.12**  $Kp$ -velocity correlation coefficients for time shifts in the range –24–48 hours. The correlations for the whole solar-wind data (solid), for solar-wind streams without CMEs (dashed) and for CMEs only (dotted) are plotted. The data used is the 3-hour maximum of the minutely high resolution OMNI data from the period 1981–2016.

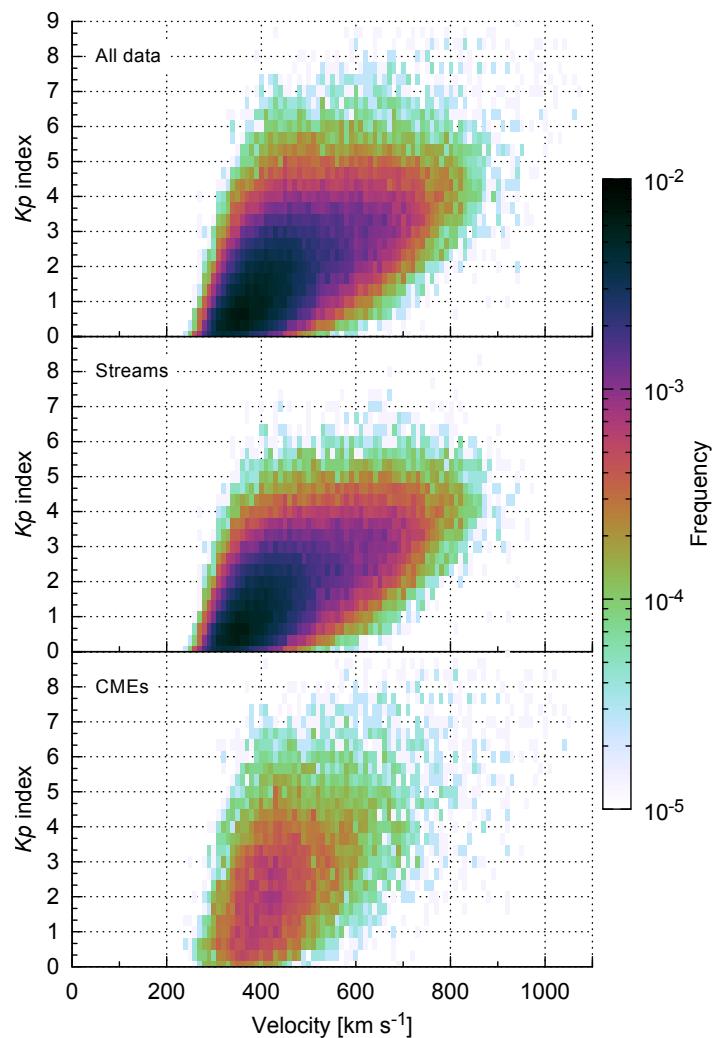
using the CME related periods from the SWS list as a filter. Their frequency distributions show that the CME share is rising in faster solar wind until eventually in the region above about 900 km s $^{-1}$  there only exist CMEs, see Fig. 4.11.

The CME part of the data is correlated with the  $Kp$  index independently from the remaining solar-wind streams, see Fig. 4.12. The correlation for CME related data is lower than that for the regular solar wind (all data). Its maximal correlation coefficient with a value of 0.51 is without time shift, see Table 4.1. The solar-wind streams show a higher correlation with  $Kp$  and the maximal coefficient of 0.66 has a positive time shift of 9 hours, that is, the  $Kp$  index forecasts the velocity of solar-wind streams 9 hours in advance.

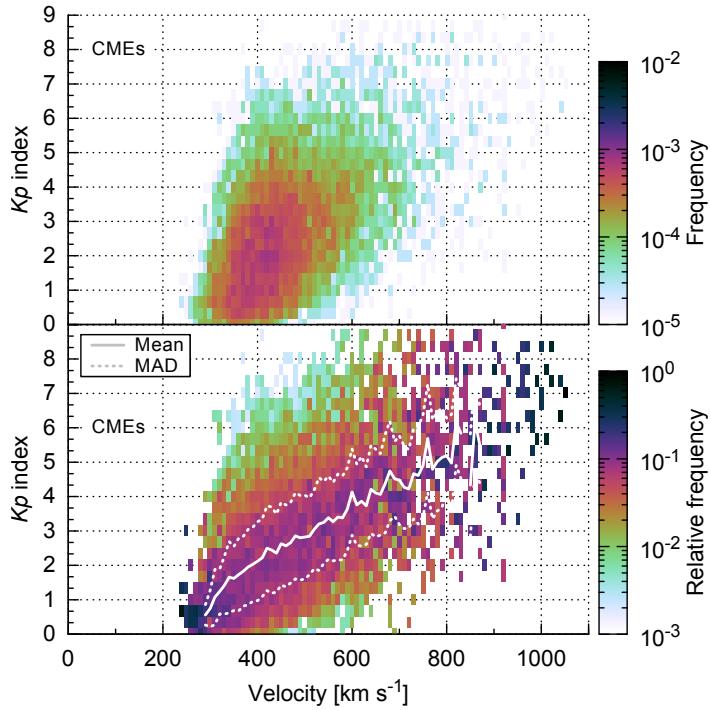
The positive time shift can be explained with the occurrence of interaction regions followed by high speed streams (HSS). When a slow solar-wind stream is followed by a fast one, the compression at their interface leads to enhanced solar-wind densities and magnetic field strengths. The peak velocity of a HSS naturally appears after the interaction region. Therefore the  $Kp$ -impact from the enhanced magnetic field is correlated with the higher velocity of the HSS, yielding the observed positive time shift.

#### 4.5.5 Functional dependency for CME velocity

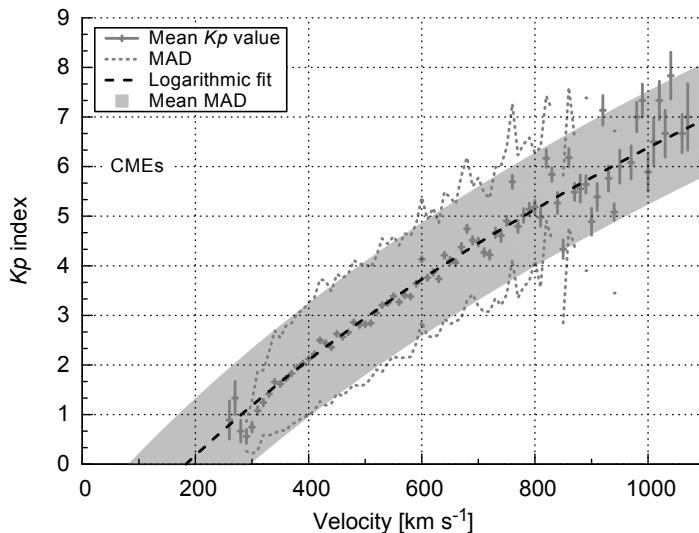
The general  $Kp$ -velocity dependency in the solar wind is apparent in the tilt of its distribution, see top panel of Fig. 4.13. The distribution is inclined to positive values and very broad. The comparison with the CME data shows that  $Kp$  values >6 and velocities >850 km s $^{-1}$  are almost always associated with CME related periods, see middle and bottom panel of Fig. 4.13.



**Figure 4.13**  $Kp$ -velocity distributions for all solar-wind data, for solar-wind streams and for CMEs. The data used is the 3-hour maximum of the minutely high resolution OMNI data. The SWS list from Richardson & Cane (2012) is used for the CME and stream separation. The bin size is  $10 \text{ km s}^{-1}$  and  $1/3 Kp$  unit respectively.



**Figure 4.14** CME part of the  $Kp$ -velocity distribution (same as third panel of Fig. 4.13) and its relative distribution per velocity interval with the mean  $Kp$  values (solid) and their mean absolute deviation (dotted). The bin size is  $10 \text{ km s}^{-1}$  and  $1/3 Kp$  unit respectively. The CME part of the OMNI data from the period 1981–2016 is obtained using the SWS list from Richardson & Cane (2012).



**Figure 4.15** Mean  $Kp$  values (+) and MAD values (dotted) per velocity interval for the CME part of the data. The error bars represent the relative data count. The logarithmic fit (dashed) is plotted with a mean MAD band (shaded area). The function (4.10) is used for the weighted fit.

To find a functional relation for the mean  $Kp$  value, I look at the relative frequencies per velocity interval, which are plotted in the bottom panel of Fig. 4.14. The mean  $Kp$  value seems to scale almost linear with the solar-wind velocity. The MAD of the mean has a mean size of about  $1.1 Kp$  units.

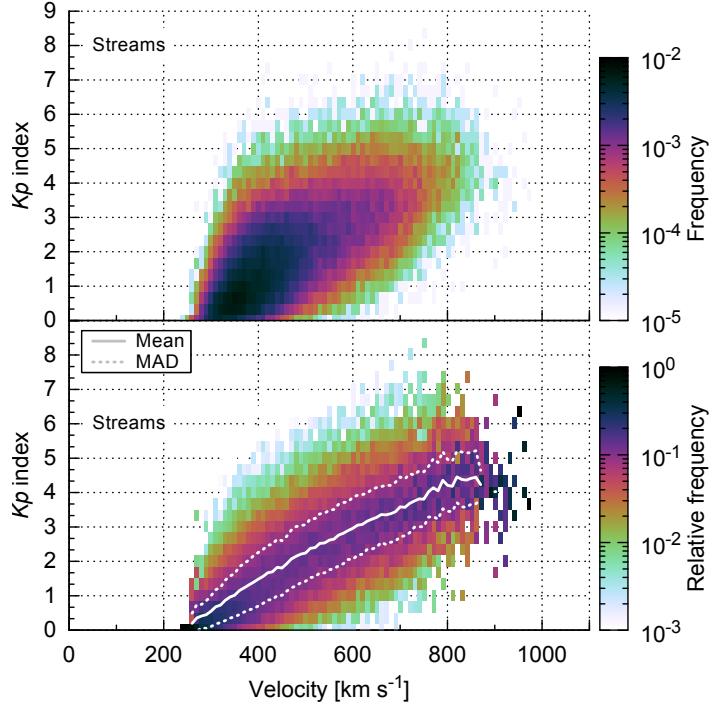
Again, as the  $Kp$  index has a quasi-logarithmic scaling, a logarithmic function is the obvious choice for the fitting process. Thus, the logarithmic function

$$f(x) = a \cdot \ln(x + x') + y' \quad (4.10)$$

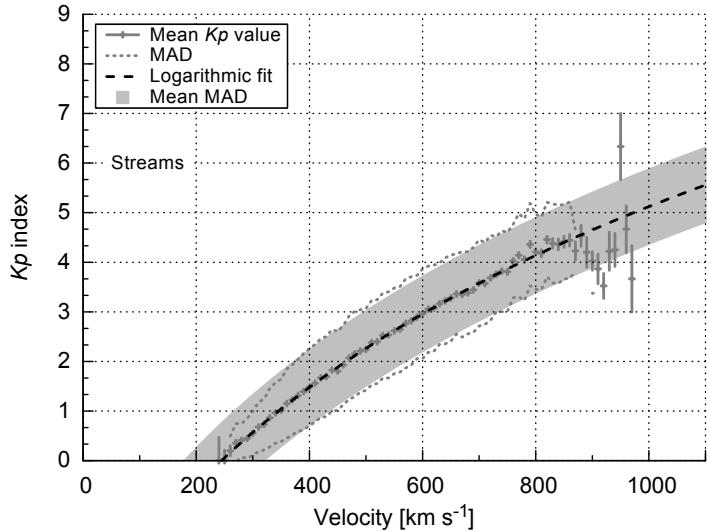
is used for the fit, with the scaling factor  $a$ , the location parameter  $x'$ , and the vertical shifting parameter  $y'$ . The resulting fit is plotted in Fig. 4.15 and its parameters are  $a = 10.6(34)$ ,  $b = -73(28)$ , and  $x' = 8.1(43) \times 10^2$ , with the velocity in units of  $[\text{km s}^{-1}]$ . The MAD is about  $1.1 Kp$  units. This leads to the CME dependency function

$$Kp(v) = 10.6 \cdot \ln(v + 810) - 73, \quad (4.11)$$

which can be used to forecast the  $Kp$  index from the estimated CME arrival velocity.



**Figure 4.16** Stream part of the  $K_p$ -velocity distribution (similar to second panel of Fig. 4.13, but with the data shifted by 9-hours) and its relative distribution per velocity interval with the mean  $K_p$  values (solid) and their mean absolute deviation (dotted). The bin size is  $10 \text{ km s}^{-1}$  and  $1/3 K_p$  unit respectively. The stream part of the OMNI data from the period 1981–2016 is obtained using the SWS list from Richardson & Cane (2012).



**Figure 4.17** Mean  $K_p$  values (+) and MAD values (dotted) per velocity interval for the stream part of the data, shifted by 9 hours. The error bars represent the relative data count. The logarithmic fit (dashed) is plotted with a mean MAD band (shaded area). The function (4.10) is used for the weighted fit.

#### 4.5.6 Functional dependency for stream velocity

The analysis procedure in this section is similar to that in the previous section. The correlation coefficient is higher for solar-wind stream velocities when the data is shifted by 9 hours, see Fig. 4.12. I use the shifted data and look at the relative frequencies per velocity interval in order to find a functional dependency for the mean  $K_p$  value, see bottom panel of Fig. 4.16. Again, the mean  $K_p$  value scales almost linear with the velocity. The MAD of the mean has a mean size of about  $0.7 K_p$  units.

Again, I use the logarithmic function (4.10) for the fitting process. The resulting fit is plotted in Fig. 4.17 and the fit parameters are  $a = 5.88(38)$ ,  $y' = -3.70(29) \times 10^1$ , and  $x' = 2.99(49) \times 10^2$ , with the velocity in units of  $[\text{km s}^{-1}]$ . The MAD is about  $0.7 K_p$  units. This leads to the solar-wind stream dependency function

$$K_p(v) = 5.88 \cdot \ln(v + 299) - 37.0, \quad (4.12)$$

which can be used to forecast the  $K_p$  index from the estimated stream velocity, e.g., obtained from remote coronal hole analyses.

## 4.6 Discussion and summary

The following results/relations are obtained from the analyses:

- solar activity:  $Kp$ -SSN relation with half a  $Kp$  unit as error
- seasonal variations: about 1  $Kp$  unit
- solar-wind nowcast:  $Kp$ - $vB_z$  relation (average and worst case)
- CME forecast:  $Kp$ -velocity relation (average and worst case)
- stream forecast:  $Kp$ -velocity relation (average and worst case)

CMEs can be faster than the maximal velocities included in the OMNI data. Instrumental effects (specify...) lead to data gaps during these periods. Yet, CME speeds of up to XX km/s at 1 au were observed in-situ (cite paper ref.). A CME speed of 2000 km s<sup>-1</sup> would lead on average to a theoretical  $Kp$  of 12.17, however, the  $Kp$  scale is capped at 90. This maximal value is reached already at a velocity of 1489 km/s.

Solar-wind streams cannot be faster than 1000 km/s (limited coronal temperatures/never observed (cites?)). That is why streams on average provoke  $Kp$  values below 50.

comparison:  
 $Kp$ -velocity correlation  
similar to Elliott et al. (2013); different data time period, resolution and averaging method (3-hour maximum of 1 min data)

## 4.7 Applications and outlook

'scientists develop an advanced prototype space weather warning system to ensure the operation of telecommunication and navigation systems on Earth to the threat of solar storms' AFFECTS

Prototype/precursor relations are integrated into applications developed within the Advanced Forecast For Ensuring Communications Through Space (AFFECTS) project which ran from 2011 to 2013. The following services, accessible via the AFFECTS website<sup>9</sup>, contain results from this  $Kp$  study (all links existent in 2017-11-19):

- DSCOVR real-time solar-wind with  $Kp$  plot [http://www.affects-fp7.eu/rssfeeds/ace\\_ap\\_plot/ace\\_realtime\\_ap\\_plot.png](http://www.affects-fp7.eu/rssfeeds/ace_ap_plot/ace_realtime_ap_plot.png)
- DSCOVR real-time solar-wind and  $Kp$  forecast plot [http://www.affects-fp7.eu/rssfeeds/ace\\_ap\\_forecast\\_plot/ace\\_realtime\\_ap\\_CH\\_GFT\\_plot.png](http://www.affects-fp7.eu/rssfeeds/ace_ap_forecast_plot/ace_realtime_ap_CH_GFT_plot.png)
- RSS L1 Kp Alert: [http://www.affects-fp7.eu/rssfeeds/rssfeed\\_kp/rssfeed\\_kp.xml](http://www.affects-fp7.eu/rssfeeds/rssfeed_kp/rssfeed_kp.xml)
- RSS L1 GNSS Alert: [http://www.affects-fp7.eu/rssfeeds/rssfeed\\_gnss/rssfeed\\_gnss.xml](http://www.affects-fp7.eu/rssfeeds/rssfeed_gnss/rssfeed_gnss.xml)
- RSS L1 Aurora Alert: [http://www.affects-fp7.eu/rssfeeds/rssfeed\\_aurora/rssfeed\\_aurora.xml](http://www.affects-fp7.eu/rssfeeds/rssfeed_aurora/rssfeed_aurora.xml)

Further applications of resulting  $Kp$ -relations:

- CME  $Kp$  impact (part of UGOE DDC)
- iPhone app L1 Alerts (Solar wind latest 2-hour extreme values and derived forecast values): <http://www.affects-fp7.eu/app-services/L1-Alerts/dataL1Alerts.txt> <https://itunes.apple.com/au/app/affects/id893579846>
- Android app L1 Alerts... <https://play.google.com/store/apps/details?id=com.affects.forecasts>
- has SW-Display  $Kp$  forecast??
- exclude?  $Kp$  forecast calculation: [http://www.astro.physik.uni-goettingen.de/~mvenzmer/kp\\_forecast\\_calculation/kp\\_forecast\\_calculation.php](http://www.astro.physik.uni-goettingen.de/~mvenzmer/kp_forecast_calculation/kp_forecast_calculation.php)

make real links...

reduce list to  $Kp$ -related services...

<sup>9</sup>AFFECTS website (existent in 2017-11-19): <http://www.affects-fp7.eu/services/>

#### **4. Solar wind and CME influence on the magnetosphere**

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outlook:

Separate structures such as CIRs and HCSs for their  $K_p$ -impact separately...

All provided web links in this work were existent in [date].

CME  $K_p$  impact as part of DDC

- $K_p$  nowcast with L1 solar wind measurements (L1 alerts, disseminated as RSS feeds; integrated in smartphone app and space weather display)
- Forecast of the possible CME impact on the Earth's magnetosphere ( $K_p$  index) from the predicted CME arrival velocity (integrated in UGOE CME forecast chain (aka DDC))

#### **4.8 notes...**

-> example events CIR/HSS and CME

What kind of solar wind structures create the individual regions in this distribution?

What is their individual contribution to the  $K_p$  ranges (e.g. high  $K_p$ : CMEs 70% and CIRs 30%)?

ACE solar wind time series and event list (ACE OPTIMAP "Zeitreihe"-events)

How can the impact field strength of CMEs be forecasted (V->B correlation for CMEs)?

Internal solar wind correlations: B-V correlation

ACE MAGSWE 64 s data -> yearly overlay plot

rt data errors/gaps... vs science data (see paper  $K_p$  as V replacement)

DSCOVR as replacement was launched on 11 Februar 2015. It is NOAA's SWPC real-time solar-wind prime source since 27 July 2016.<sup>10</sup>

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<sup>10</sup><http://www.swpc.noaa.gov/products/real-time-solar-wind>

## 5 Empirical solar-wind model for the inner heliosphere

### 5.1 Introduction

The analyses in the previous chapter are focused on the solar wind's influence on the magnetosphere – this chapter changes the main focus to the solar wind upstream of the magnetosphere, in a first step down to a solar distance of 0.3 au and then even further down to the region around  $10 R_{\odot}$ , close to the solar wind's origin near the Sun. The solar wind's evolution on its way to 1 au from the near-Sun region is modeled with the goal of predicting the solar wind environment for the upcoming PSP mission.

context of motivation in thesis and paper introduction and context of results in thesis

This chapter is constructed as follows, the PSP mission, its scientific goals, and the spacecraft are described, I introduce the analyses done in the publication [Venzmer & Bothmer \(2017\)](#), which is a major part of this chapter, an improvement to the magnetic field solar distance dependency is derived, which upgrades that from our article, other things, and further an outlook is given.

The major part of this chapter is published as “Solar-wind predictions for the Parker Solar Probe orbit” in [Venzmer & Bothmer \(2017\)](#) (replace arXiv cite with aanda's), which is referred to as ‘the paper’ in this work. The article, published in Astronomy and Astrophysics (A&A), is included following this chapter, denoted as [Chapter 6](#), and **not yet** reproduced with permission, © ESO.

The analyses described in the paper were entirely done by me, as well as the tables, figures and equations. My coauthor Volker Bothmer contributed to the text and the anonymous referee helped clarifying a few aspects. The text was further improved by the A&A language editor Joshua Neve.

### 5.2 Parker Solar Probe mission

motivation written in [McComas et al. \(2007\)](#)

mission goals (see paper + [Fox et al. \(2015\)](#))

A photo of PSP during testing is shown in [Figure 5.1](#) and an illustration of PSP flying near the Sun is shown in [Figure 5.2](#).

orbit figure? ref. to distance figure?

WISPR instrument

CGAUSS project – context of this work in project objectives

Sun angular diameter comparison, see presi S<sup>3</sup>

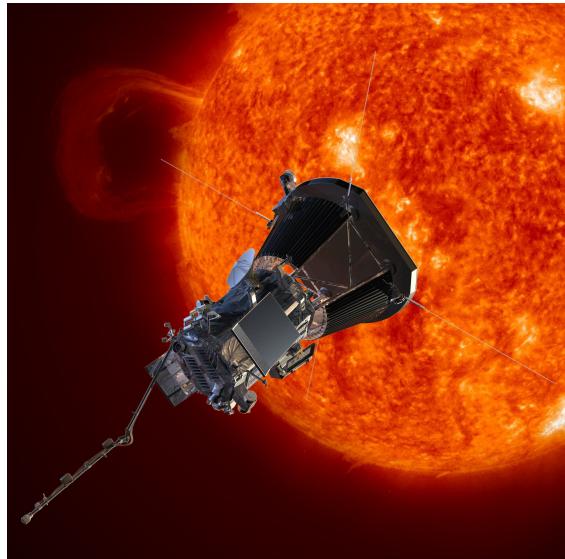
### 5.3 Paper content

We obtained lognormal representations of the frequency distributions' shapes of the four key solar wind parameters magnetic field strength, proton velocity, density and temperature. We derived analytical relations for the parameters' solar activity dependencies and for their solar distance scaling. An empirical solar wind model was built from the combination of the obtained frequency distributions, SSN dependence relations and solar distance dependence functions, representing the solar wind's solar activity and distance behavior. This empirical model was fed with SSN predictions and extrapolated to the orbit of PSP. We estimated solar wind median values during PSP's first perihelion and modeled the values for PSP's closest perihelia.

In order to derive the solar wind environment for the PSP orbit, finally the general solar wind model derived in the previous sections will be extrapolated to the PSP orbit, taking into account predictions of the SSN.



**Figure 5.1** PSP in the Acoustic Test Chamber at NASA’s Goddard Space Flight Center in November 2017. Credit: [NASA/Johns Hopkins APL/Ed Whitman](#), 2017.



**Figure 5.2** Artist’s concept of PSP near the Sun. Credit: [NASA/Johns Hopkins APL](#), 2015.

### 5.3.1 Solar distance dependency—theory

B-field radial profile:  $B \propto r^{-1.5}$ ; exponent between -1 and -2

Magnetic field model (Parker1958) (the equations are quoted in the next section)

velocity radial profile:  $V \propto r^0$  (constant; Parker)

maxwellian distribution? difference to lognormal...

density radial profile:  $N \propto r^{-2}$

simple view: For a spherical constant velocity mass outflow, a per distance squared law is expected, because of the mass flux conservation per solid angle for different distances. Measurements up to the outer heliosphere confirm the  $r^{-2}$  dependency (1–38 au by Voyager 2, ([Belcher et al. 1993](#)) newer paper?)

temperature radial profile:  $T \propto r^{-1.5}$

at larger distances (specify...) heating outbalances the adiabatic temperature part (adiabatic cooling vs. pickup proton and stream–interaction heating; 1–68 au by Voyager 2; [Richardson & Smith \(2003\)](#))

solar wind ram pressure  $p_{\text{ram}} = \rho V^2$

## 5.4 Improvement to the magnetic field solar distance dependency

note: comparison plot between models in range 0–20 au...

In our article, we scaled the magnetic field strength via a power-law function and obtained a solar-distance dependency proportional to  $r^{-1.662}$ . We also noted there that the model’s near-Sun field magnitude, extrapolated to PSP’s closest perihelion, will be lower than the actual values to be found. However, it was a simplified approach – in the following I present a procedure, leading to an improved distance dependency, which also accounts for the contributions of the individual field vector components. The new distance dependency, extrapolated to the PSP orbit and combined with the solar activity dependency described in the paper, yields 8 % higher values at the first perihelion and 32 % higher values at the 22nd perihelion.

A more accurate distance dependency for the model is derived in the following.

The coronal magnetic field near the Sun rotates rigidly, holding on to the coronal plasma. At the solar-wind source surface (at around  $2.5 R_{\odot}$ ), where the thermal plasma pressure overcomes the magnetic pressure, the magnetic field gets radially transported outwards, maintaining only its radial vector component  $\mathbf{B}_r$ . From there

on, the solar rotation begins to shear the magnetic field, building up a longitudinal component  $\mathbf{B}_\phi$  as well. The solar-wind magnetic field model formulated by Parker (1958) has the following components in spherical coordinates ( $\theta$  is the colatitude):

$$\mathbf{B}_r(r) = B_0 \left( \frac{r_0}{r} \right)^2 \cdot \mathbf{e}_r, \quad (5.1)$$

$$\mathbf{B}_\phi(r) = -B_0 \left( \frac{r_0}{r} \right)^2 \cdot \frac{\omega r \sin \theta}{v_{sw}} \cdot \mathbf{e}_\phi, \quad (5.2)$$

$$\mathbf{B}_\theta(r) = 0 \cdot \mathbf{e}_\theta. \quad (5.3)$$

$B_0$  represents the radial field component at the solar distance  $r_0$ . The solar surface equatorial angular rotation rate  $\omega$  and the solar-wind velocity  $v_{sw}$  are involved as well. From these equations it can be seen that  $\mathbf{B}_r$  scales with increasing solar distance with  $r^{-2}$ , as it is expected for a spherical outflow, and  $\mathbf{B}_\phi$  scales with  $r^{-1}$  as expected for a two-dimensional point source. In-situ observations support the component's scaling according to these theoretical exponents, although in slow solar wind the scaling for  $\mathbf{B}_\phi$  deviates somewhat from theory (Mariani et al. 1978).

From the magnetic field's absolute value

$$B(r) = \sqrt{\mathbf{B}_r^2 + \mathbf{B}_\phi^2 + \mathbf{B}_\theta^2}, \quad (5.4)$$

$$B(r) = \sqrt{\left( B_0 \left( \frac{r_0}{r} \right)^2 \right)^2 + \left( -B_0 \left( \frac{r_0}{r} \right)^2 \cdot \frac{\omega r \sin \theta}{v_{sw}} \right)^2}, \quad (5.5)$$

it is apparent that the magnetic field strength does not scale with a simple power law. If the solar dipole axis tilt to the solar rotation axis is neglected and the radial field component  $B_0$  is set to be in the equatorial plane at  $r_0 = 1$  au, then  $\theta = 90^\circ$  and therefore

$$B(r) = B_0 \cdot \sqrt{r^{-4} + \left( \frac{\omega r}{v_{sw}} \right)^2 r^{-4}}, \quad (5.6)$$

with the distance  $r$  in units of [au].

The magnetic field angle in the solar equatorial plane is distance dependent and is calculated via

$$\phi_B(r) = \arctan \left( -\frac{\omega \cdot r}{v_{sw}} \right). \quad (5.7)$$

The angle becomes  $\phi_B(1 \text{ au}) = -46.23^\circ$  when using the Sun's equatorial angular velocity  $\omega_{eq} = 14.37^\circ \text{ d}^{-1}$  (for more details on solar rotation see appendix [Section A.1](#)) and the median solar-wind velocity  $v_{sw} = 416 \text{ km s}^{-1}$  from the paper.

During solar cycle minimum, the solar wind in the equatorial plane outside the source surface originates from polar regions at about  $\pm 60^\circ$  heliolatitude. This leads to a slightly underwound Parker spiral, because of the slower rotation rate at higher latitudes (Banaszkiewicz et al. 1998). Using the differential rotation rate  $\omega(\pm 60^\circ) = 13.69^\circ \text{ d}^{-1}$  (see appendix [Equation A.1](#)), the field angle becomes  $\phi_B(1 \text{ au}) = -44.84^\circ$ .

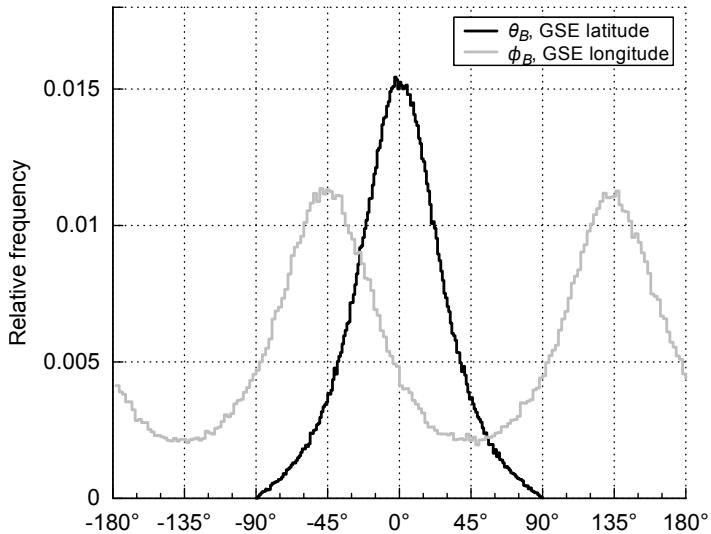
Neglecting the solar rotation axis tilt to the ecliptic normal...

So, in the ecliptic at a solar distance of 1 au, the Parker spiral's observed magnetic field angle  $\phi_B$  is centered most of the time at  $-45^\circ$  or in the opposite direction at  $135^\circ$ .

This is indeed measured at 1 au and is apparent from the angle's frequency distribution, using OMNI data of the time period 1963–2016, see [Figure 5.3](#).

For  $\phi_B$  being in average centered around these two directions, both vector components  $B_r$  and  $B_\phi$  have to be of equal amplitude. It can be seen from Equations 5.4 and 5.6 that this leads to

$$B(1 \text{ au}) = B_0 \cdot \sqrt{2} \quad \text{with} \quad \left( \frac{\omega \cdot 1 \text{ au}}{v_{sw}} \right) = 1. \quad (5.8)$$



**Figure 5.3** Frequency distributions of the magnetic field angles  $\theta_B$  and  $\phi_B$  in GSE coordinates. The frequencies are based on the hourly OMNI data during the period 1963–2016.

However this way,  $\omega$  and  $v_{sw}$  are treated as constants and their variations with time are neglected.

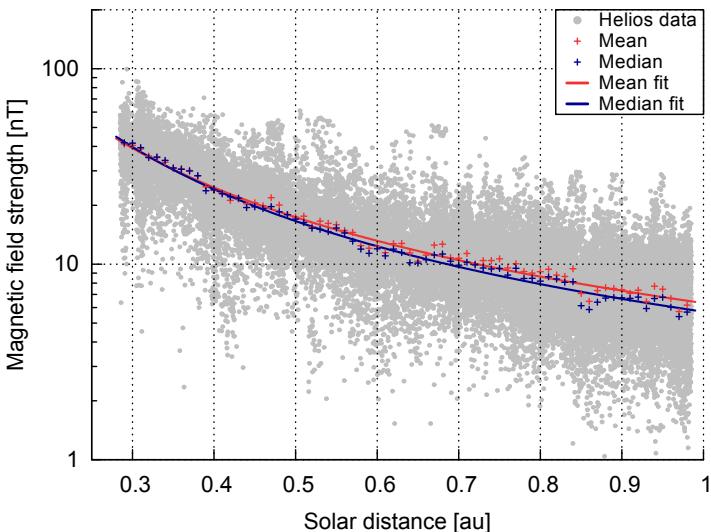
Considering the longitudinal field component, the magnetic field strength's distance dependency is derived in a similar way to that in the paper, see [Section 6.4](#). Also, the same Helios data set is used for the fit as is in the paper.

In order to get an analytical representation of the radial dependence of the magnetic field, the function

$$x(r) = a \cdot \sqrt{(r^{e_1})^2 + (r^{e_2})^2} \quad (5.9)$$

with the scaling parameter  $a$ , the exponents  $e_1$  and  $e_2$ , is used in a least squares regression fit. From the theoretical considerations sketched above, the expected fit parameter values are:  $a \approx \frac{B(1 \text{ au})}{\sqrt{2}}$ ,  $e_1 \approx -2$ , and  $e_2 \approx -1$ .

The resulting fit curves for mean and median field strength are plotted with respect to solar distance in [Figure 5.4](#). In the Helios distance region 0.3–1.0 au, the fit curves are very similar to those in the paper – as they are expected to be. This is why this graph is visually almost indistinguishable to the corresponding one in the paper (paper [Section 6.4](#), Figure 7). The resulting fit parameters are presented in [Table 5.1](#)<sup>1</sup>.



**Figure 5.4** Magnetic field strength with respect to solar distance. The mean and median per 0.01 au data bin and their fit curves are plotted as well. The hourly Helios data has a native distance resolution of 0.01 au, thus, to make the distribution visible in this plot, I added a random distance value of up to  $\pm 0.005$  au.

<sup>1</sup> Concerning the error notation I adhere to the parentheses notation documented in the “Guide to the expression of uncertainty in measurement” (GUM) published by [Joint Committee for Guides in Metrology \(2008\)](#), where the numbers in parentheses are the errors on the corresponding last digits of the quoted value.

**Table 5.1** Fit parameter values for the curve fits (Equation 5.9) and the distribution fit (eq XX), derived from the combined Helios 1 and 2 data. The numbers in parentheses are the errors on the corresponding last digits of the quoted value. The crossing distance indicates where the median and mean fits intersect each other. This distance is calculated numerically and that is why the error is only estimated.

Fit	Factor $a$	Exponents		Crossing distance [au]
		$e_1$	$e_2$	
Curve	Median	4.04(13)	-1.852(25)	-0.97(23)
	Mean	4.47(12)	-1.740(18)	-0.99(23)
Distribution	Median	3.833(27)	-1.858(42)	-1.32(12)
	Mean	4.081(29)		-

Here, the WSSR slightly improved (6 % for the median and 9 % for the mean) compared to the simple power-law function  $x(r) = d \cdot r^e$  in Venzmer & Bothmer (2017). However, the mean and median fit curves still cross each other at a similar value as in the paper.

The obtained fit parameter values are similar to the theoretical values – however, the larger exponent  $e_1$  leads to a less steep slope near the Sun.

...and it can be fitted via a lognormal function

from paper:

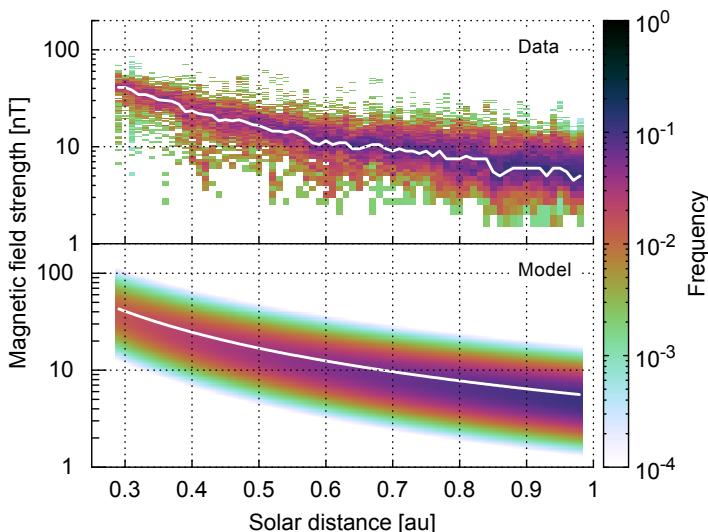
'The mean and median velocity fit exponents acquired from the Helios data are very similar, which indicates that they can be kept identical so that the basic shape of the frequency distribution does not change with distance.

The crossing points limit the regions where the distribution's shapes can still be considered lognormal.

In order to still fit and extrapolate lognormal functions with the data, we assume that the shapes can be considered lognormal at all distances. For the frequency distribution fit function to be discussed in the following paragraph, we reduce the fit exponents  $e_{\text{med}}$  and  $e_{\text{avg}}$  to only one.

Implementing the power law distance dependency (refeq:) into the lognormal function (refeq:), we get the fit parameters  $d'_{\text{med}}$ ,  $d'_{\text{avg}}$  and the common exponent  $e'$ .

fix mean and median exponents and make a distribution fit. see fit distribution in Figure 5.5 and resulting fit parameters in Table 5.1.



**Figure 5.5** Frequency distribution of the solar wind magnetic field strength with respect to solar distance. Plotted are the binned Helios data and the square-root power-law lognormal fit model with their median values (white lines).

from paper:

'In order to estimate the solar-wind environment for the PSP orbit, we combine the results from the solar-wind frequency distributions' solar-activity relationships and their distance dependencies derived from the OMNI and Helios data. The result is an empirical solar-wind model for the inner heliosphere which is then extrapolated to the PSP orbit.'

## 5. Empirical solar-wind model for the inner heliosphere

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lated to the PSP orbit in Sect. refsec:.'

The result of this analysis can be used to scale the SSN-relation derived in the paper:

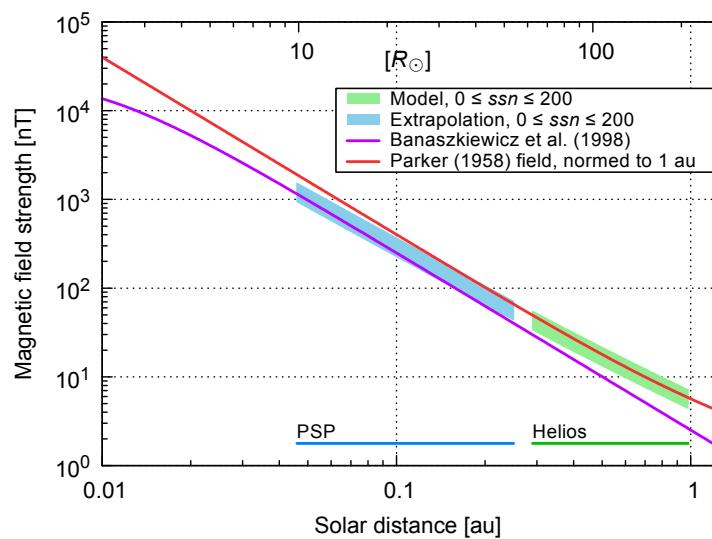
$$B(ssn, r) = \frac{B(ssn)}{\sqrt{2}} \cdot \sqrt{(r^{e_1})^2 + (r^{e_2})^2}. \quad (5.10)$$

The resulting equation, combined with the values obtained from the solar activity analysis in the paper [Section 6.3](#), gives

$$B_{\text{med}}(ssn, r) = (0.0131 \text{ nT} \cdot ssn + 4.29 \text{ nT}) \cdot \sqrt{(r^{-1.86})^2 + (r^{-1.3})^2}, \quad (5.11)$$

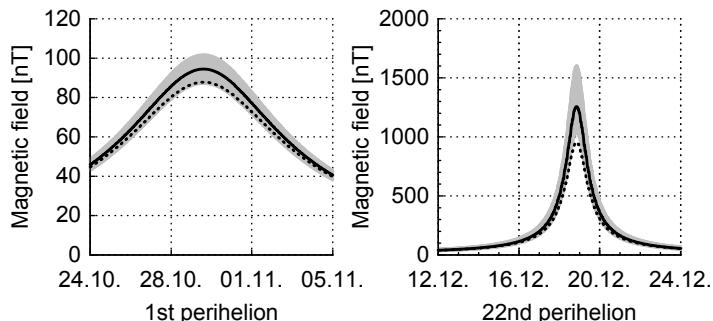
$$B_{\text{avg}}(ssn, r) = 1.0879 \cdot B_{\text{med}}(ssn, r). \quad (5.12)$$

This magnetic field strength model is extrapolated to PSP's orbital range in [Figure 5.6](#).



**Figure 5.6** Radial extrapolation of the solar-wind magnetic field strength to the PSP orbit region. The median value from the model, obtained from Helios and OMNI measurements, is extrapolated to the PSP region for SSN values between solar minimum and maximum, that is,  $0 \leq ssn \leq 200$ . The lower edges of the shaded areas correspond to solar minimum, the upper edges to solar maximum. Also plotted are the radial dependencies of the analytic DQCS magnetic field model for solar minimum (violet) from [Banaszkiewicz et al. \(1998\)](#) and the Parker field model (red).

forecast to PSP orbit and mission time, see [Figure 5.7](#)

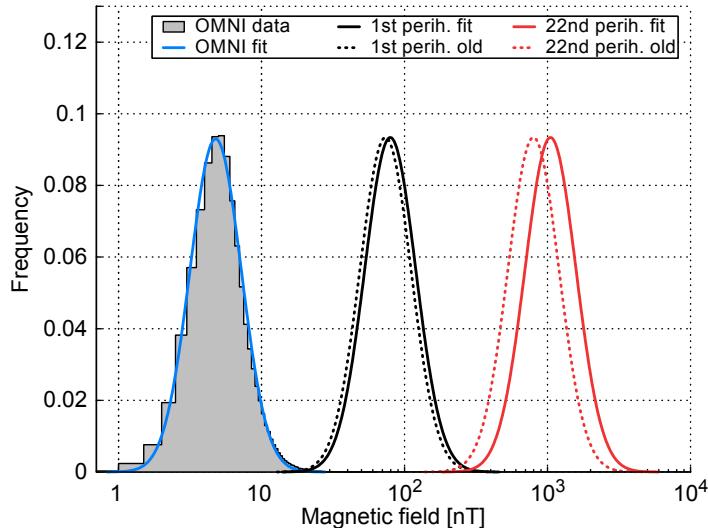


**Figure 5.7** Estimated solar-wind parameter medians (solid) and their error bands (gray area) during 12 days in 2018 and 2024 with PSP's first perihelion at about 0.16 au and PSP's 22nd (the first closest) perihelion at 0.046 au. The prediction from [Venzmer & Bothmer \(2017\)](#) is indicated as well (dotted).

The estimated magnetic field strength median value of 94 nT for the first perihelion is 8 % higher than that in the paper. However, the median value of 1241 nT for the first closest perihelion is 32 % higher.

The estimated frequency distributions of the solar-wind magnetic field strength at PSP's 1st and 22nd (first closest) perihelion are plotted in [Figure 5.8](#).

The newly derived dependency relation can be used to replace that found in the paper.



**Figure 5.8** Frequency distributions of the solar-wind magnetic field strength (OMNI data) and those estimated with the solar-wind model for PSP's 1st and 22nd (first closest) perihelion. In this plot the frequencies of both extrapolated curves are scaled for visibility to the same height as the 1 au distribution. The predictions from Venzmer & Bothmer (2017) are indicated as well (dotted).

## 5.5 Outlook

Currently, the solar-wind model described in this chapter is purely empirical and its four solar-wind quantities are characterized independently from each other. Now in further steps, theoretical relations connecting the parameters could be introduced to make the model self-consistent. For example, flux conservation could be implemented into the radial distance dependencies, relating the two parameters density and velocity (see section XX), and also the velocity within the magnetic field's  $B_\phi$ -component (Equation 5.2) could be respected as a variable (not as a constant as it is done in the previous section).

PSP's in-situ measurements, starting in fall 2018, will eventually reveal how accurate the predictions of this model are.

Data captured from spacecraft that studied Mercury (perihelion distance of 0.3 au), such as Mariner 10 and MESSENGER, could be included to refine the distance dependency of the solar-wind model.

- further investigations should be done into structure extrapolations
- outward extension of model seems feasible (e.g., to Mars)

### 5.5.1 flux conservation

conserved quantities:

- momentum conservation... VBbookp112
- flux conservation...

With consideration of continuity, the mass flux per solid angle has to be constant:  $\dot{m} = \text{const}$   
conserved quantities:

- mass flux:  $\dot{m} = \rho v A$  (with mass density  $\rho$ , velocity  $v$  and solid angle  $A$ )
- particle fluxes (proton flux, electron flux, etc.)
- proton flux:  $j_p = n_p v_p A$  (with proton density  $n_p$  and proton velocity  $v_p$ )

(with proton mass density  $\rho = n_p m_p$  (with proton number density  $n_p$  and proton mass  $m_p$ )).

the individual radial dependencies for a spherical radial outflow are:  
 $A(r) \propto r^2 \rightarrow A/r^2 = \text{const}$

and assuming an exponential dependency,

$$n_p(r) = n_0 r^{c_n}, \\ v(r) = v_0 r^{c_v}$$

$$j_p = \text{const} \quad (5.13)$$

$$n_p v_p A = \text{const} \quad (5.14)$$

$$n_0 r^{c_n} v_0 r^{c_v} r^2 = \text{const} \quad (5.15)$$

$$r^{c_n} r^{c_v} r^2 = \text{const} \quad (5.16)$$

$$\Rightarrow c_n + c_v + 2 = 0 \quad (5.17)$$

$$c_n + c_v = -2 \quad (5.18)$$

an increasing velocity should result in a steeper density...

validity of mass flux continuity: within the heliosphere mass to energy conversion and vice versa is negligible, but there can be flux from and to higher latitudes as the Helios data is localized to a small latitude range in the ecliptic plane.

larger errors should be located near CMEs and CIRs (nonradial flows from interactions)

there is a proton flux difference between slow and fast solar wind streams (see book Schwenn1990 p. 146)

estimate the possible size of error:

(constant mass flux only for mean)

$$c_n = -2.114$$

$$c_v = 0.0990$$

$$c_n + c_v = -2.024$$

difference to -2 is 0.024

## 5.6 Literature

Schwenn1983 intro -> sw-averaging comment (beer and wine) (cite him...)

see Hellinger2013 p.1353

see astro70/CGAUSS/dropbox\_presis/... (presi 1.07 Inside Helios-Origins and Evolution-Salem.ppt -> Helios reloaded; radial functions for all parameters)

see Balogh1999 from p. 162 (Helios CIR results)

see Marsch1999... (model constraints)

On solar wind acceleration and SPP proposition: McComas2007

Parker1963 book, p. 75 -> isothermal expansion figure

Motivational question: What is the evolution of the solar wind parameters/structures before arriving at Earth?  
what is meant by the term evolution?

## 5.7 Seasonal solar wind variations

seasonal variation by month

quantify variation amplitudes

see [Figure 5.9](#)

see [Figure 5.10](#)

derived exponent values from simple trigonometric fit on monthly values:

$$c_n = -2.234$$

maybe figure?

expected influence from Earth's perihelion/aphelion (see Appendix...) distance vs observations

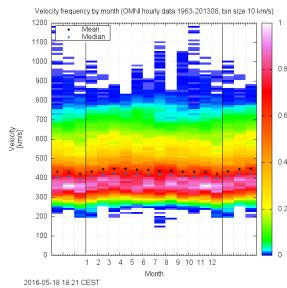
we expect for the mean proton density (scaling law  $n(r) \propto r^{-2.114}$ ):

$$n(0.983 \text{ au}) = 7.098 \text{ cm}^{-3}$$

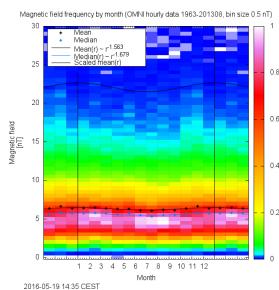
$$n(1 \text{ au}) = 6.845 \text{ cm}^{-3}$$

$$n(1.017 \text{ au}) = 6.605 \text{ cm}^{-3}$$

we expect for the magnetic field strength (paper scaling law  $n(r) \propto r^{-1.662}$ ):



**Figure 5.9** Diagram of the velocity frequency by month for the period 1963/01–2013/08. Mean and median values are shown as well.



**Figure 5.10** Diagram of magnetic field frequency by month for the period 1963/01–2013/08. Mean and median values are shown as well as the expected course from the solar distance variation (obtained from Helios data).

$$B(0.983 \text{ au}) = 5.870 \text{ nT}$$

$$B(1 \text{ au}) = 5.705 \text{ nT}$$

$$B(1.017 \text{ au}) = 5.547 \text{ nT}$$

## 5.8 Latitude dependency

refer to Ulysses [Figure 2.16](#)

Ulysses swoops polar plots...

see Schwenn1990's Fig. 3.14

see also [Schwenn \(1990\)](#) p. 127

see also [Richardson et al. \(1995\)](#)

Balogh et al. (1999) p. 162 ff (origin and formation of CIRs in inner heliosphere with Helios data; latitude V dependence)

Helios latitude; see [Figure 5.11](#)

with the exponential dependencies to 1 au projected solar wind parameters; there are only small changes with latitude in the range  $-7.25\text{--}7.25^\circ$

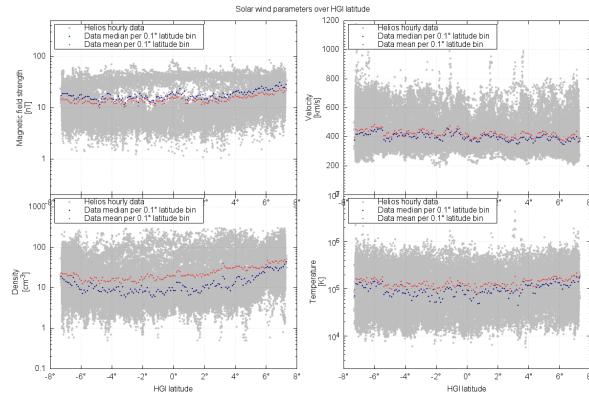
have a look on distribution widths...

dependence from latitude in interval  $-7.25\text{--}7.25^\circ$  in Helios data negligible?, see [Figure 5.12](#).  
estimate error ranges from latitude influence...

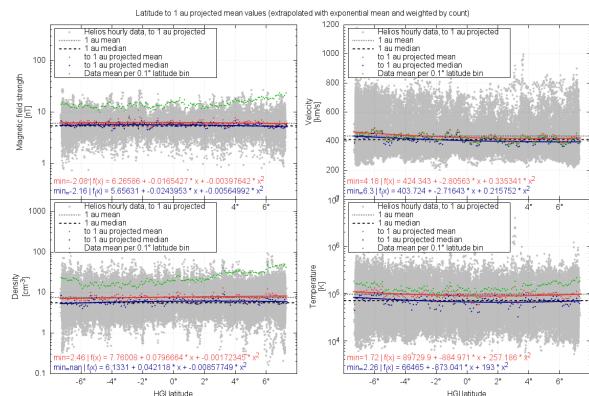
...plot Ulysses data into plot?

influence from latitude variation in data negligible? (see Ulysses [Figure 2.16](#) in introduction). Helios probes within ecliptic => variation span equal to solar tilt:  $-7.25\text{--}7.25^\circ$ ; solar tilt/obliquity to ecliptic:  $i_\odot = 7.25^\circ$  (Sun

## 5. Empirical solar-wind model for the inner heliosphere



**Figure 5.11** The four solar wind parameter's HGI latitude dependency. Their mean and median values per  $0.1^\circ$  bin are plotted as well. random jitter...



**Figure 5.12** Solar wind parameters projected to 1 au with respect to latitude. And their mean values, including weighted fit. add projected median... random jitter...

fact sheet: <http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html>

big part of Helios data is from latitudes  $> \pm 5^\circ$ , see Figure XX (data count over latitude) and see Figure 3.8 (Helios orbit polar plane in data section)

## 5.9 Radial evolution of solar wind structures

Helios event lists HSSs, SLOWs, CIRs, CMEs...; event lists for all Helios data  
see Liu2004 for Helios ICME list and radial dependencies of  $B$ ,  $n$ ,  $T$  and  $v$ ...

$200 \text{ km s}^{-1}$  slow solar wind at  $10 R_\odot$  is in agreement with blob measurements from Wang2000

very slow sw (VSSW) gets accelerated; see Sanchez-Diaz2016:

radial diameter of MCs increase between  $0.3 \text{ au}$  and  $4.3 \text{ au}$  proportional to the distance as  $r^{0.8}$  (Bothmer & Schwenn 1998)

MC central axial magnetic field strength radial density dependence  $B = 18.1 r^{-1.64}$  Leitner et al. (2007)

MC average diameter  $D = 0.23 r^{1.14}$  Leitner et al. (2007)

sw structure marked plots

structure extrapolations

replace paper with actual published A&A version...

# Solar-wind predictions for the Parker Solar Probe orbit

## Near-Sun extrapolations derived from an empirical solar-wind model based on Helios and OMNI observations

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### ABSTRACT

**Context.** The Parker Solar Probe (PSP) (formerly Solar Probe Plus) mission will be humanity's first in situ exploration of the solar corona with closest perihelia at 9.86 solar radii ( $R_\odot$ ) distance to the Sun. It will help answer hitherto unresolved questions on the heating of the solar corona and the source and acceleration of the solar wind and solar energetic particles. The scope of this study is to model the solar-wind environment for PSP's unprecedented distances in its prime mission phase during the years 2018–2025. The study is performed within the Coronagraphic German And US SolarProbePlus Survey (CGAUSS) which is the German contribution to the PSP mission as part of the Wide-field Imager for Solar PRobe (WISPR).

**Aims.** We present an empirical solar-wind model for the inner heliosphere which is derived from OMNI and Helios data. The German-US space probes Helios 1 and Helios 2 flew in the 1970s and observed solar wind in the ecliptic within heliocentric distances of 0.29–0.98 au. The OMNI database consists of multi-spacecraft intercalibrated in situ data obtained near 1 au over more than five solar cycles. The international sunspot number (SSN) and its predictions are used to derive dependencies of the major solar-wind parameters on solar activity and to forecast their properties for the PSP mission.

**Methods.** The frequency distributions for the solar-wind key parameters, magnetic field strength, proton velocity, density, and temperature, are represented by lognormal functions. In addition, we consider the velocity distribution's bi-componental shape, consisting of a slower and a faster part. Functional relations to solar activity are compiled with use of the OMNI data by correlating and fitting the frequency distributions with the SSN. Further, based on the combined data set from both Helios probes, the parameters' frequency distributions are fitted with respect to solar distance to obtain power law dependencies. Thus an empirical solar-wind model for the inner heliosphere confined to the ecliptic region is derived, accounting for solar activity and for solar distance through adequate shifts of the lognormal distributions. Finally, the inclusion of SSN predictions and the extrapolation down to PSP's perihelion region enables us to estimate the solar-wind environment for PSP's planned trajectory during its mission duration.

**Results.** The CGAUSS empirical solar-wind model for PSP yields dependencies on solar activity and solar distance for the solar-wind parameters' frequency distributions. The estimated solar-wind median values for PSP's first perihelion in 2018 at a solar distance of 0.16 au are 87 nT, 340 km s<sup>-1</sup>, 214 cm<sup>-3</sup> and 503 000 K. The estimates for PSP's first closest perihelion, occurring in 2024 at 0.046 au (9.86  $R_\odot$ ), are 943 nT, 290 km s<sup>-1</sup>, 2951 cm<sup>-3</sup>, and 1 930 000 K. Since the modeled velocity and temperature values below approximately 20  $R_\odot$  appear overestimated in comparison with existing observations, this suggests that PSP will directly measure solar-wind acceleration and heating processes below 20  $R_\odot$  as planned.

**Key words.** solar wind – sun: heliosphere – sun: corona

### 1. Introduction

From observations of cometary tail fluctuations, Biermann (1951) inferred the presence of a continuous flow of particles from the Sun. With his theoretical solar-wind model, Parker (1958) formulated the existence of the solar wind even before the first satellites measured it in situ in 1959 (Gringauz et al. 1960; Neugebauer & Snyder 1966). The idea of a space mission flying through the solar corona dates back to the founding year of NASA in 1958 (McComas et al. 2008). Since then several space missions have measured the solar wind in situ at a wide range of heliocentric distances. In the case of Voyager 1, this was as far away as 140 au<sup>1</sup> in October 2017, having crossed the heliopause into interstellar space at a distance of 121 au (Gurnett et al. 2013). Various spacecraft have provided a wealth of solar-wind measurements near Earth's orbit, with WIND (Leping et al. 1995; Ogilvie et al. 1995), SOHO (Domingo et al.

1995), ACE (Stone et al. 1998) and DSCOVR (Burt & Smith 2012) currently providing observations while orbiting around the L1 point 1.5 million km ahead of Earth in the sunward direction. Additional measurements at other solar distances were provided by planetary missions to Venus and Mercury, such as PVO (Colin 1980) or MESSENGER (Belcher et al. 1991). Ulysses was the first probe that orbited the Sun out of the ecliptic plane and thus could measure solar wind even at polar latitudes (McComas et al. 1998). The in situ solar-wind measurements closest to the Sun to date were made by the Helios missions. Helios 1, launched in 1974, reached distances of 0.31 au. Helios 2, launched two years later, approached the Sun as close as 0.29 au (Rosenbauer et al. 1977). The NASA Parker Solar Probe<sup>2</sup> (PSP), formerly Solar Probe Plus, six years after its planned launch date in mid 2018, will reach its closest perihelia at a distance of 9.86 solar radii ( $R_\odot$ ), that is, 0.0459 au (Fox et al. 2015). This distance will

<sup>1</sup> <https://voyager.jpl.nasa.gov/>

<sup>2</sup> <http://parkersolarprobe.jhuapl.edu/>

be achieved through seven Venus gravity assists with orbital periods of 88–168 days. In its prime mission time 2018–2025 PSP provides 24 orbits with perihelia inside 0.25 au (Fox et al. 2015). Even its first perihelion, 93 days after launch in 2018, will take PSP to an unprecedented distance of 0.16 au ( $35.7 R_{\odot}$ ). In comparison, the ESA Solar Orbiter mission with a planned launch in February 2019 will have its closest perihelia at 0.28 au (Müller et al. 2013).

The key PSP science objectives are to “trace the flow of energy that heats and accelerates the solar corona and solar wind, determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind, and explore mechanisms that accelerate and transport energetic particles” as stated in Fox et al. (2015). To achieve these goals, PSP has four scientific instruments on board: FIELDS for the measurement of magnetic fields and AC/DC electric fields (Bale et al. 2016), SWEAP for the measurement of flux of electrons, protons and alphas (Kasper et al. 2016), IS $\odot$ IS for the measurement of solar energetic particles (SEPs) (McComas et al. 2016) and WISPR for the measurement of coronal and inner heliospheric structures (Vourlidas et al. 2016).

The study presented in this paper is undertaken in the Coronagraphic German And US SolarProbePlus Survey (CGAUSS) project, which is the German contribution to the PSP mission as part of the Wide-field Imager for Solar PRobe (WISPR). WISPR will contribute to the PSP science goals by deriving the three-dimensional structure of the solar corona through which the in situ measurements are made to determine the sources of the solar wind. It will provide density power spectra over a wide range of structures (e.g., streamers, pseudostreamers and equatorial coronal holes) for determining the roles of turbulence, waves, and pressure-balanced structures in the solar wind. It will also measure the physical properties, such as speed and density jumps of SEP-producing shocks and their coronal mass ejection (CME) drivers as they evolve in the corona and inner heliosphere (Vourlidas et al. 2016). In order to help optimize the WISPR and PSP preplanning of the science operations, knowledge of the expected solar-wind environment is needed. For this purpose the solar-wind environment is extrapolated down to the closest perihelion of  $9.86 R_{\odot}$  distance to the Sun using in situ solar-wind data from the Helios probes and near 1 au data from various satellites compiled in the OMNI solar-wind database.

Generally, two types of solar wind are observed in the heliosphere – slow and fast streams (Neugebauer & Snyder 1966; Schwenn 1983). Slow solar wind has typical speeds of  $<400 \text{ km s}^{-1}$  and fast solar wind has speeds  $>600 \text{ km s}^{-1}$  (Schwenn 1990, p. 144). Their different compositions and characteristics indicate different sources and generation processes (McGregor et al. 2011b). Fast streams are found to originate from coronal holes as confirmed by Ulysses’ out-of-ecliptic measurements (McComas et al. 1998). The source of slow wind, and its eventually different types (Schwenn 1983), is still a subject of controversial discussions because several scenarios are possible to explain its origin from closed magnetic structures in the solar corona, such as intermittent reconnection at the top of helmet streamers and from coronal hole boundaries (Kilpua et al. 2016). The occurrence frequency of these slow and fast streams varies strongly with solar activity and their interactions lead to phenomena such as stream interaction regions which may persist for many solar rotations (“co-rotating” interaction regions) if the coronal source regions are quasi-stationary (Balogh et al. 1999). Embedded in the slow and fast solar-wind streams are transient flows of CMEs – the faster ones driving shock waves ahead (Gosling et al. 1974). Their rate follows the solar activity

cycle and varies in near 1 au measurements between only one CME every couple of days during solar cycle minima up to multiple CMEs observed over several days at times of solar maxima, that is, the CME-associated flow share of the solar wind raises from about 5 % up to about 50 % (Richardson & Cane 2012).

It is not known which specific solar-wind type or structure PSP will encounter at a given time during its mission, therefore we extrapolate the probability distributions of the major solar-wind parameters from existing solar-wind measurements and take solar cycle dependencies into account. As a baseline we describe the solar-wind environment through the key quantities of a magnetized plasma: magnetic field strength, density and temperature. Furthermore, the bulk flow velocity is the defining parameter of the two types of solar wind. Solar-wind quantities, like flux densities, mass flux, and plasma beta, can be directly derived from these four parameters. In the analyses, we treat the solar wind as a proton plasma – the average helium abundance is about 4.5 % and in slow wind at solar cycle minimum is even less than 2 % (Feldman et al. 1978; Schwenn 1983; Kasper et al. 2012).

Our approach is to obtain analytical representations of the shapes of the solar-wind parameter’s frequency distributions in Sect. 2, of their solar activity dependence in Sect. 3 and of their solar distance scaling in Sect. 4. The solar-wind parameters’ frequency distributions and solar activity dependence is derived from near-Earth solar wind and sunspot number (SSN) time series with a duration of almost five solar cycles. Their distance dependency is derived from Helios solar-wind measurements covering more than two thirds of the distance to the Sun and more than half a solar cycle. From a combination of the obtained frequency distributions, SSN dependence functions, and solar distance dependence functions, a general solar-wind model is built in Sect. 5, representing the solar activity and distance behavior. Finally, this empirical model is fed with SSN predictions and extrapolated to PSP’s planned orbital positions in Sect. 6.

## 2. Frequency distributions of the solar-wind parameters

The solar-wind parameters are highly variable due to short-term variations from structures such as slow and fast wind streams, interaction regions, and CMEs, whose rate and properties depend on the phase of the solar activity cycle. Hence, for deriving characteristic frequency distributions for the solar-wind parameters, measurements over long-term time spans are needed. The abundance of the near-Earth hourly OMNI data set is ideally suited for this purpose, because to date it spans almost five solar cycles.

The OMNI 2 data set (King & Papitashvili 2005) combines solar-wind magnetic field and plasma data collected by various satellites since 1963, currently by WIND and by ACE. This intercalibrated multi-spacecraft data is time-shifted to the nose of the Earth’s bow shock. The data is obtained from the OMNI-Web interface<sup>3</sup> at NASA’s Space Physics Data Facility (SPDF), Goddard Space Flight Center (GSFC). In this study the whole hourly data until 31 December 2016 is used, starting from 27 November 1963 (for the temperature from 26 July 1965). The data coverage of the different parameters is in the range 67–74 %, corresponding to a total duration of 36–40 years. We note that a test-comparison of hourly averaged data with higher-time-resolution data for the available shorter time span 1981–2016 did not show significant differences in our results. According to the

<sup>3</sup> <http://omniweb.gsfc.nasa.gov/>

OMNI data precision and maximal parameter ranges we specify bin sizes of 0.5 nT for the magnetic field strength, 10 km s<sup>-1</sup> for the velocity, 1 cm<sup>-3</sup> for the density and 10 000 K for the temperature. The frequency distributions of the solar-wind magnetic field strength, proton velocity, density and temperature are shown in Fig. 1. The solar-wind magnetic field strength is in the range 0.4–62 nT, the velocity in the range 156–1189 km s<sup>-1</sup>, the density in the range 0–117 cm<sup>-3</sup>, the temperature in the range 3450–6.63 × 10<sup>6</sup> K, and the mean data values are at 6.28 nT, 436 km s<sup>-1</sup>, 6.8 cm<sup>-3</sup> and 1.05 × 10<sup>5</sup> K. These ranges and mean values are as statistically expected from previous analyses of near 1 au solar-wind data (e.g., Table 3.3 in Bothmer & Daglis (2007, p. 39)). Much higher or lower peak values at 1 au have been observed in extraordinary events, such as the 23 July 2012 CME with a speed of over 2000 km s<sup>-1</sup> and a peak field strength of about 100 nT that was observed by STEREO A (Russell et al. 2013), or the solar-wind disappearance event observed in May 1999 with density values even down to 0.2 cm<sup>-3</sup> (Lazarus 2000).

The frequency distributions of the solar-wind parameters, magnetic field strength, proton density, and temperature, can be well approximated by lognormal distributions, whereas the proton velocity's frequency has a differing shape, as shown in Veselovsky et al. (2010). We investigate how well all four solar-wind parameters' frequency distributions can be represented by lognormal functions, which we use in the process of a least squares regression fitting. The lognormal function,

$$W(x) = \frac{1}{\sigma \sqrt{2\pi} x} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right), \quad (1)$$

depends on the location  $\mu$  and the shape parameter  $\sigma$ . Changes in  $\mu$  affect both the horizontal and vertical scaling of the function whereas  $\sigma$  influences its shape. The distribution's median  $x_{\text{med}}$  and mean  $x_{\text{avg}}$  (average) positions are easily interpreted and are directly calculated from  $\mu$  and  $\sigma$ :

$$x_{\text{med}} = \exp(\mu) \iff \mu = \ln(x_{\text{med}}), \quad (2)$$

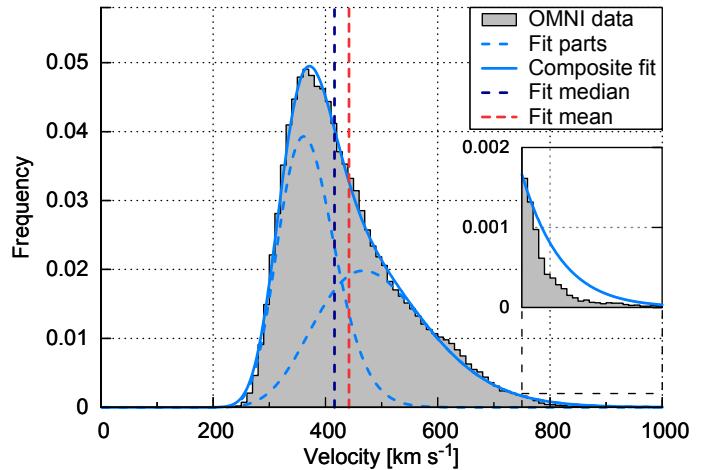
$$x_{\text{avg}} = \exp\left(\mu + \frac{\sigma^2}{2}\right) \iff \sigma = \sqrt{2 \ln\left(\frac{x_{\text{avg}}}{x_{\text{med}}}\right)}. \quad (3)$$

It is apparent that the mean is always larger than the median. Replacing the variables  $\mu$  and  $\sigma$  with these relations, the lognormal function (1) becomes

$$W(x) = \frac{1}{2 \sqrt{\pi \ln\left(\frac{x_{\text{avg}}}{x_{\text{med}}}\right)} x} \exp\left(-\frac{\ln^2\left(\frac{x}{x_{\text{med}}}\right)}{4 \ln\left(\frac{x_{\text{avg}}}{x_{\text{med}}}\right)}\right). \quad (4)$$

The values of  $x_{\text{med}}$  and  $x_{\text{avg}}$  obtained from fitting the individual solar-wind frequency distributions are listed in Table 1.

From visual inspection, the resulting fit curves describe the shape of the magnetic field strength, the density and the temperature distributions well, as can be seen in Fig. 1. However, for the velocity, the fit function appears not to be as good in describing the measured distribution's more complex shape around its peak and in the higher velocity range. This also can be inferred from the sum of absolute residuals (SAR) between data and fit, listed in Table 1 as a percentage of the distribution area, being almost three times larger than those from the other parameters. In order to find a better fit result for the velocity distribution, we assume that the velocity distribution can be made up of at least two overlapping branches (McGregor et al. 2011a). Therefore a



**Fig. 2.** Velocity frequency distribution (same as in Fig. 1) and its compositional lognormal fit. The fit's median and mean values and its two fit parts are indicated as well. The inset is a zoomed-in view of the high value tail of the distribution.

compositional approach is chosen by combining two lognormal functions (4), involving more fit variables:

$$W_{\text{II}}(x) = c \cdot W_1(x) + (1 - c) \cdot W_2(x). \quad (5)$$

The balancing parameter  $c$  ensures that the resulting function remains normalized as it represents a probability distribution. The fitting of  $W_{\text{II}}(x)$  to the velocity's frequency distribution yields the values of the now five fit parameters ( $c$ ,  $x_{\text{med},1}$ ,  $x_{\text{avg},1}$ ,  $x_{\text{med},2}$  and  $x_{\text{avg},2}$ ) as listed in Table 1 together with the median and mean values of the composed distribution, which can be derived by solving

$$\int W_{\text{II}}(x) dx = 0 \quad \text{and} \quad \int x W_{\text{II}}(x) dx = 0. \quad (6)$$

This more complex fit function is more accurate in describing the velocity's frequency distribution as shown in Fig. 2. Thus in the following Sections we keep the double lognormal ansatz for all velocity frequency fits.

For the bulk of the solar wind these static lognormal functions describe the parameters' distributions well. The abnormally high parameter values in the distribution functions can be attributed to shock/CME events in agreement with the results of the OMNI solar-wind investigations by Richardson & Cane (2012). The simple lognormal fit functions underestimate the frequencies in their high-value tails, except for the temperature's tail which is overestimated, as seen in the insets of Fig. 1. This appears to be because CMEs do not come with abnormally high temperatures, but rather with temperatures lower than those of the average solar wind (Forsyth et al. 2006). The velocity's compositional lognormal fit only slightly overestimates its tail as seen in the inset of Fig. 2. The slow and fast part contribute almost equally ( $c \approx 0.5$ ) to the long-term velocity distribution function.

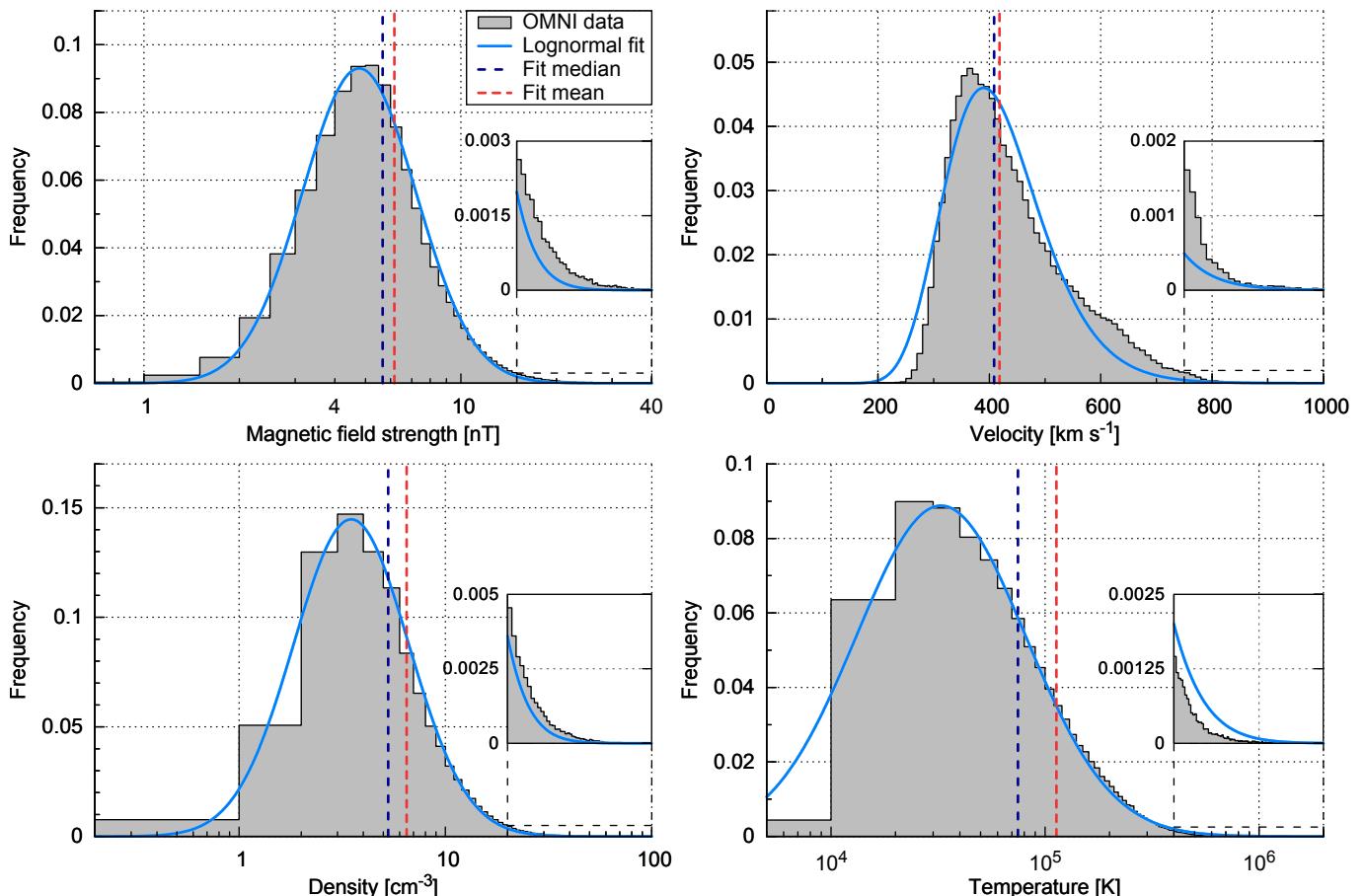
### 3. Solar activity dependence of the solar-wind frequency distributions

In the next step we investigate how the long-term solar-wind distribution functions presented in the previous section depend on general solar activity. Therefore we examine their correlation with the SSN, being a commonly used long-term solar activity

**Table 1.** Resulting fit coefficients from the fitting of the lognormal function (4) to the shape of the solar-wind parameters' frequency distributions from near 1 au OMNI hourly data. For the velocity, the fit parameters of the double lognormal function (5) are also listed, as well as the median and mean values of the resulting velocity fit. The numbers in parentheses are the errors on the corresponding last digits of the quoted value. They are calculated from the estimated standard deviations of the fit parameters. For each parameter, the sum of absolute residuals between data and fit (in percentage of the distribution area) is also listed.

Parameter	Median $x_{\text{med}}$	Mean $x_{\text{avg}}$	Balance $c$	SAR [%]
Magnetic field [nT]	5.661(16)	6.164(18)	–	6.83
Velocity [ $10^2 \text{ km s}^{-1}$ ]	4.085(19)	4.183(20)	–	18.69
Density [ $\text{cm}^{-3}$ ]	5.276(24)	6.484(34)	–	6.48
Temperature [ $10^4 \text{ K}$ ]	7.470(17)	11.301(32)	–	5.78
Velocity [ $10^2 \text{ km s}^{-1}$ ]	$W_1$ 3.68(20)	5.00(14)	0.504(62)	–
	$W_2$ 4.16(14) <sup>a</sup>	3.72(20)	–	–
	$W_{\text{II}}$ 4.42(14) <sup>a</sup>	4.42(14) <sup>a</sup>	–	4.20

Notes. <sup>(a)</sup> Error estimates derived from the individual fit part errors.



**Fig. 1.** Frequency distributions of the four solar-wind parameters and their lognormal fits derived from the hourly OMNI data set. The histograms have bins of 0.5 nT, 10 km s<sup>-1</sup>, 1 cm<sup>-3</sup> and 10 000 K. The fits' median and mean values are indicated as well. The insets show zoomed-in views of the high-value tails of the distributions.

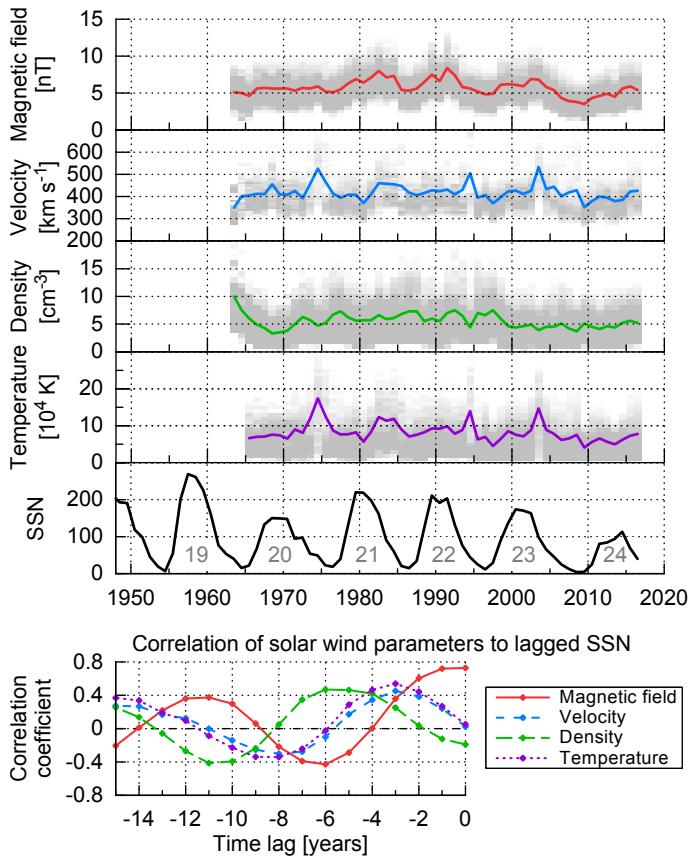
index, and determine the time lags with the highest correlation coefficients.

For the correlations we fit lognormal functions to the frequency distributions as in Sect. 2, but implement linear relations to the yearly SSN, allowing shifting of the distribution functions with SSN. For the velocity the approach is different insofar as its two components are kept fixed and instead their balance is modified with the changing SSN. Thus we obtain solar-activity-dependent models for the frequency distributions of all four solar-wind parameters.

The international sunspot number (1963–2016) is provided by the online catalog<sup>4</sup> at the World Data Center – Sunspot Index and Long-term Solar Observations (WDC-SILSO), Solar Influences Data Analysis Center (SIDC), Royal Observatory of Belgium (ROB).

Yearly medians of the solar-wind parameters and the yearly SSN together with the solar cycle number are shown in the upper part of Fig. 3. The reason for correlating the SSN to the

<sup>4</sup> <http://www.sidc.be/silso/>

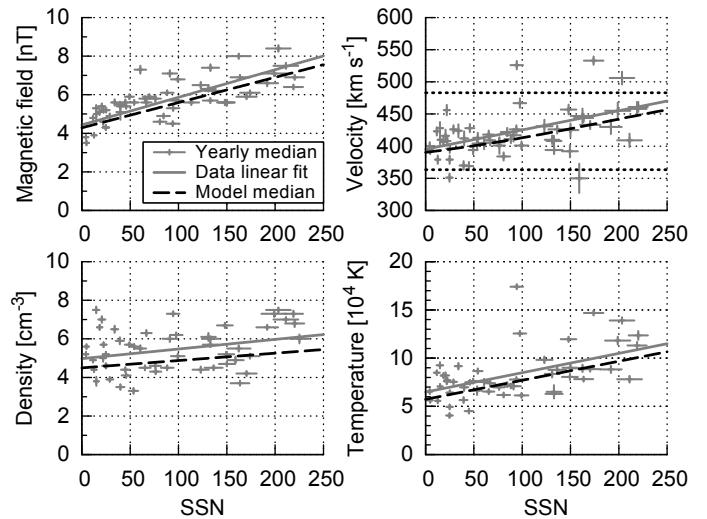


**Fig. 3.** Solar-wind parameter yearly frequencies (gray shading) with yearly medians (lines) derived from OMNI data and the yearly SSN from the SILSO World Data Center (1963–2016) with solar cycle number (top). Their correlation coefficients with the yearly SSN are calculated for time lags back to –15 years (bottom).

solar-wind median values is because the position of a lognormal function is defined by its median. The data are averaged to yearly values to avoid seasonal effects during the Earth's orbit around the Sun caused by its variations in solar latitude and distance. The solar-wind velocity, density, and temperature depend on the state of the solar cycle (Schwenn 1983). For instance the fast solar wind occurs at times when polar coronal holes extend to lower latitudes, a typical feature of the declining phase of the solar cycle as pointed out by Bothmer & Daglis (2007, p. 75, Fig. 3.52). Therefore the solar-wind velocity, density, and temperature maxima exhibit time lags relative to the SSN maxima.

The correlation coefficients of the solar wind parameters with the yearly SSN shown in the bottom part of Fig. 3 are calculated for time lags back to –15 years to cover a time span longer than a solar cycle. As expected, the amplitudes of the variations in the correlations of all parameters decline with increasing time lag and show a period of about 11 years. The highest correlation coefficient of 0.728 to the SSN is found for the magnetic field strength; it has no time lag. This finding is anticipated because the SSN is found to be directly proportional to the evolution of the photospheric magnetic flux (Smith & Balogh 2003). Velocity and temperature show time lags of 3 years with peak correlation coefficients of 0.453 and 0.540. The density with a correlation coefficient of 0.468 has a time lag of 6 years, which is in agreement with the density anticorrelation to the SSN reported by Bougeret et al. (1984).

Next we create solar-activity-dependent analytical representations of the solar wind frequency distributions. This is achieved



**Fig. 5.** Solar-wind parameter medians with respect to the lagged SSN. The yearly data medians (+) with their weighted linear fit (solid lines) are obtained from OMNI data. The error bars denote the SSN standard deviation and the relative weight from the yearly data coverage. The SSN-dependent median (dashed lines) is derived from the lognormal model fit. For the velocity the median is derived from the SSN-weighting (9) of the slow and fast model parts (dotted lines), whose magnitudes are SSN independent.

by shifting the median positions of the lognormal distributions as a linear function of the SSN. To enable these shifts, we add a linear SSN dependency to the median,

$$x_{\text{med}}(ssn) = a_{\text{med}} \cdot ssn + b_{\text{med}}, \quad (7)$$

using a factor to the SSN  $a_{\text{med}}$  with a baseline  $b_{\text{med}}$ . We relate the mean with a scaling factor to the median to transfer its SSN dependency:

$$x_{\text{avg}}(ssn) = (1 + a_{\text{avg}}) \cdot x_{\text{med}}(ssn). \quad (8)$$

These relations, substituted into the lognormal function (4), lead to a new SSN-dependent function  $W'(x, ssn)$ . This function is then fitted to the yearly data, using the yearly SSN as input parameter. The SSN is offset with the individual time lags determined before for each parameter, to benefit from the higher correlation. The values of the three resulting fit coefficients ( $a_{\text{med}}$ ,  $b_{\text{med}}$  and  $a_{\text{avg}}$ ) are presented in Table 2.

Naturally, the fit models match with the general data trends, as can be seen from Fig. 4, though single year variations are not replicated by the model (e.g., the high velocity and temperature values in 1974, 1994, and 2003). The comparison of this model with the yearly data median values with respect to the lagged SSN shows that the medians obtained from the modeling have a similar slope, as shown in Fig. 5.

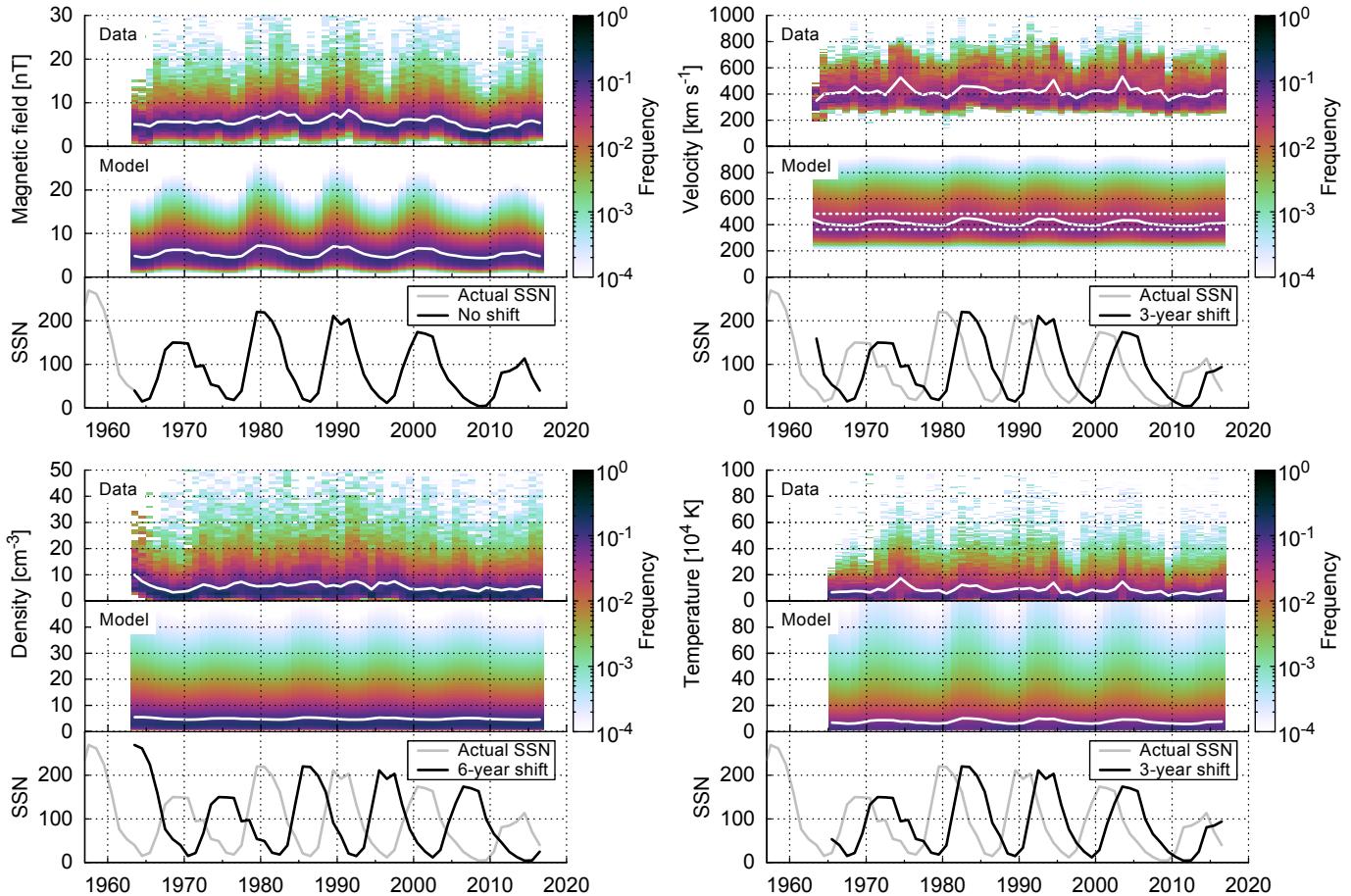
Again, the solar-wind velocity needs a special treatment because of the application of the double lognormal distribution (5). Since it is well known that slow and fast solar-wind stream occurrence rates follow the solar cycle, we keep the two velocity components' positions SSN-independent ( $x_{\text{med}} = b_{\text{med}}$ ) and vary instead their balance with the SSN:

$$c(ssn) = c_a \cdot ssn + c_b. \quad (9)$$

The fit result (see Table 2) yields a model in which three years after solar cycle minimum (SSN of zero) the contribution of slow

**Table 2.** Resulting fit coefficients from the OMNI data, based on the linear SSN dependencies (7) and (8). For the velocity the fit parameters from the double lognormal fit (5) and their balancing function (9) are given. The numbers in parentheses are the errors on the corresponding last digits of the quoted value. They are calculated from the estimated standard deviations of the fit parameters. The listed SSN time lags are used for the fits.

Parameter	Median		Mean Scaling factor $a_{\text{avg}}$	Balance		SSN lag [years]
	SSN factor $a_{\text{med}}$	Baseline $b_{\text{med}}$		SSN factor $c_a$	Baseline $c_b$	
Magnetic field [nT]	$1.309(19) \times 10^{-2}$	4.285(17)	$8.786(78) \times 10^{-2}$	—	—	0
Density [ $\text{cm}^{-3}$ ]	$3.81(25) \times 10^{-3}$	4.495(26)	$3.050(27) \times 10^{-1}$	—	—	6
Temperature [ $10^4 \text{ K}$ ]	$1.974(26) \times 10^{-2}$	5.729(19)	$6.541(28) \times 10^{-1}$	—	—	3
Velocity $[10^2 \text{ km s}^{-1}]$	$W'_1$ $W'_2$	— —	3.633(12) 4.831(81)	$1.008(37) \times 10^{-2}$ $2.31(20) \times 10^{-2}$	$-1.799(95) \times 10^{-3}$ 0.638(32)	3



**Fig. 4.** Solar wind parameter yearly data frequencies and lognormal fit models, both with their median values (white lines) over the OMNI time period 1963–2016. The corresponding yearly SSN and the shifted SSN for the models are indicated by gray and black lines. The velocity median is derived from the SSN-weighted constant lognormal parts (dotted lines).

solar wind to the overall solar wind distribution reaches a maximum value (about 64 %) and decreases with increasing SSN as shown in Fig. 6.

To investigate the amount of slow and fast wind contributions depending on solar activity, we apply the commonly used constant velocity threshold of  $v_{\text{th}} = 400 \text{ km s}^{-1}$  (Schwenn 1990, p. 144). The linear fit to the yearly data ratio and the derived model ratio show a good agreement (see Fig. 6). The to-some-degree steeper balance parameter of the double fit function used in this model cannot be compared directly with specific velocity thresholds between slow and fast solar wind. However, it appears to be a more realistic approach than just taking a specific velocity threshold for the slow and fast wind, in agreement with the overlapping nature of the velocity flows reported by McGregor et al. (2011a).

#### 4. Solar distance dependency

In order to derive heliocentric distance relationships of the bulk solar wind distribution functions, we apply and fit power law dependencies to the Helios data. We then examine how the fits may be extrapolated towards the Sun and in particular in to the PSP orbit. We use the fitting methods of Sect. 2 for the distance-binned combined data from both Helios probes. Helios' highly elliptical orbits in the ecliptic covered a solar distance range of 0.31–0.98 au in case of Helios 1 and 0.29–0.98 au in case of Helios 2. Launched during solar cycle minimum, the data of both probes cover the rise to the maximum of cycle 21, covering ~6.5 years at varying distances to the Sun.

We investigate hourly averages of the Helios data in the same way as with the OMNI data. The Helios 1 merged hourly data from the magnetometer and plasma instruments (Rosenbauer



**Fig. 6.** Ratio of slow to fast solar wind for a SSN lagged by 3 years. The yearly ratios (+) and their weighted linear fit (solid line) are obtained from OMNI data with a threshold velocity of  $v_{th} = 400 \text{ km s}^{-1}$ . The error bars denote the SSN standard deviation and the relative weight from the yearly data coverage. The model's balance parameter (9) and derived ratio (same threshold) are plotted as dashed and dotted lines.

et al. 1977) include  $\sim 12.5$  orbits for the time range 10 December 1974 to 14 June 1981, and those for Helios 2 include  $\sim 8$  orbits for the time span 1 January 1976 to 4 March 1980. The data are retrieved from the Coordinated Data Analysis Web (CDAWeb) interface at NASA's GSFC/SPDF<sup>5</sup>.

The Helios 1 magnetometer data coverage for this data set is about 43 % (i.e., 2.8 years), and that of Helios 2 amounts to 54 % (i.e., 2.3 years). The plasma data coverage is 76 % (i.e., 5.0 years) in case of Helios 1 and 92 % (i.e., 3.9 years) in case of Helios 2. Thus, using this data, we point out that its time coverage is unequally distributed over the solar cycle. Considering the data gap distributions, the amount of data during solar cycle minimum up to mid 1977, that is, the transition from minimum to maximum, covers about 68 % of this period whereas during maximum of cycle 21 data are available only 38 % of the time. This Helios data bias towards solar minimum is one reason why in this study the Helios solar wind data are not used to derive long-term frequency distributions and solar-cycle dependencies for the key solar wind parameters.

The radial dependencies of the key solar-wind parameters over the distance range 0.29–0.98 au measured by both Helios probes are plotted in Fig. 7, together with their median and mean values for different solar distances, calculated for the minimal distance resolution 0.01 au of the data set. Assuming a radial solar-wind outflow, it is expected that the distance dependence of the solar-wind parameters over the Helios data range 0.29–0.98 au can be described through power law scaling. Therefore we use the power law function,

$$x(r) = d \cdot r^e, \quad (10)$$

for the regression fit of the median and mean, with  $r$  being the solar distance in astronomical units,  $d$  the magnitude at 1 au and  $e$  the exponent. The fits are weighted through the different data counts per bin. The obtained coefficients for the median and mean power law fits ( $d_{\text{med}}$ ,  $e_{\text{med}}$ ,  $d_{\text{avg}}$  and  $e_{\text{avg}}$ ) are listed in Table 3 and their corresponding curves are shown in Fig. 7.

Our derived exponents agree with those found in existing studies from the Helios observations: Mariani et al. (1978) derived the exponents for the magnetic field strength separately for the fast and slow solar wind as  $B_{\text{fast}} \propto r^{-1.54}$  and  $B_{\text{slow}} \propto r^{-1.61}$ , ours is  $B_{\text{avg}} \propto r^{-1.55}$ . The velocity exponent  $v_{\text{avg}} \propto r^{0.049}$  matches with the values found by Schwenn (1983, 1990), who derived the distance dependencies for both Helios spacecraft separately

as  $v_{H1} \propto r^{0.083}$  and  $v_{H2} \propto r^{0.036}$ . The calculated density exponent  $n_{\text{avg}} \propto r^{-2.01}$  agrees well with the Helios plasma density model derived by Bougeret et al. (1984) yielding  $n \propto r^{-2.10}$ . The temperature exponent  $T_{\text{avg}} \propto r^{-0.79}$  is similar to those in the studies by Hellinger et al. (2011, 2013), who also derived the exponents separately for the fast and the slow solar wind:  $T_{\text{fast}} \propto r^{-0.74}$  and  $T_{\text{slow}} \propto r^{-0.58}$ .

The mean and median velocity fit exponents acquired from the Helios data are very similar, which indicates that they can be kept identical so that the basic shape of the frequency distribution does not change with distance. Conversely, the mean and median fits for the magnetic field strength cross each other at 0.339 au (see Table 3) and the mean becomes slightly lower than the median at smaller distances. Thus, below that distance the frequency distribution can no longer be well described by a lognormal function, because the mean of a lognormal function has to be larger than its median (as pointed out in Sect. 2), that is, the location of the crossing indicates that the parameter's distribution is no longer of a lognormal shape thereafter. The fits for the proton temperature show a similar behavior, having an extrapolated intersection at 0.082 au. Therefore the extrapolation of the magnetic field and temperature distribution frequencies to the PSP orbit by applying lognormal functions is limited. The crossing points limit the regions where the distribution's shapes can still be considered lognormal.

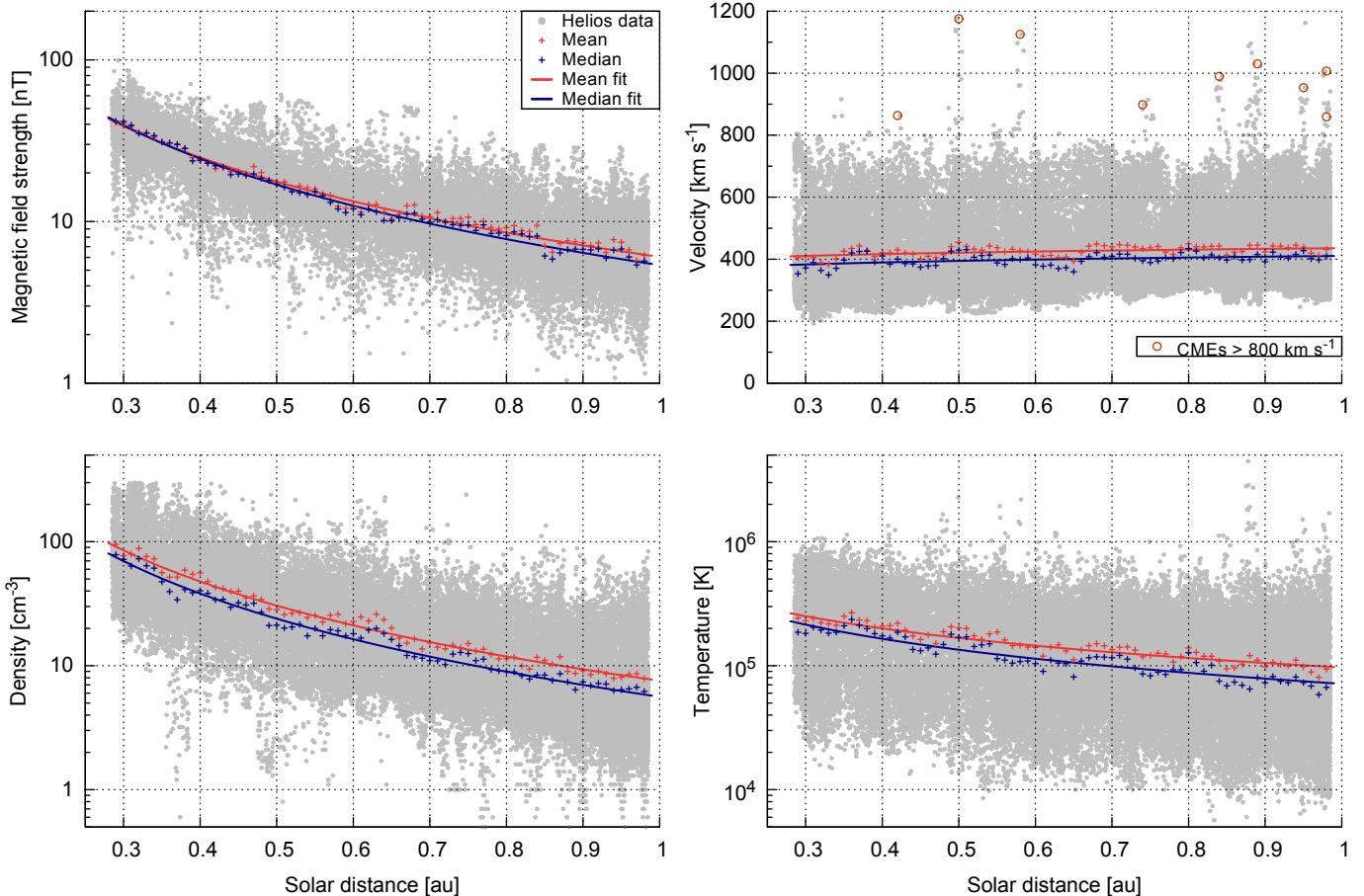
In order to still fit and extrapolate lognormal functions with the data, we assume that the shapes can be considered lognormal at all distances. For the frequency distribution fit function to be discussed in the following paragraph, we reduce the fit exponents  $e_{\text{med}}$  and  $e_{\text{avg}}$  to only one. We note that this simplification leads to slightly larger modeling errors, especially in case of the magnetic field strength.

Next we retrieve the frequency distributions of the four solar wind parameters in solar distance bins of 0.01 au, choosing the same resolution as for the OMNI data analyzed in Sect. 2 – the distributions and their median values are plotted in Fig. 8. For simplification, as mentioned before, we treat the exponents of the median and mean fit functions as being identical, using one fit parameter for both. Implementing the power law distance dependency (10) into the lognormal function (4), we get the fit parameters  $d'_{\text{med}}$ ,  $d'_{\text{avg}}$  and the common exponent  $e'$ . Again, we use the double lognormal function (5) for the velocity distribution fit – resulting in  $W''_v(x, r)$ . The additional fit parameters are the balancing parameter  $c'$  and for the second lognormal part  $d'_{\text{med},2}$  and  $d'_{\text{avg},2}$ . The resulting fit coefficients for the four solar wind parameters are presented in Table 4.

The velocity balancing parameter  $c' = 0.557$  is in good agreement with the results for the SSN dependency (9), because with a mean SSN of 59 during the Helios time period,  $c(59) = 0.53$ , as can be seen from Fig. 6.

The power law lognormal models and the power law double lognormal model for the velocity, which result from the fitting, are plotted in Fig. 8 together with their median values. The model's magnetic field strength is broader around values of 40 nT at the lower distance boundary than the data's frequency distribution implies. This behavior is expected because of the applied distance-independent shape approximation. The velocity and temperature models' upper values generally show a higher abundance than the actual data; see also zoom boxes in Figs. 1 and 2. The high-velocity tail that increases with distance arises from using the same exponent for both slow and fast components. This effect is not seen in the data; more specifically, not

<sup>5</sup> <http://spdf.gsfc.nasa.gov/>



**Fig. 7.** Helios hourly data plots of the four solar wind parameters over solar distance. The mean and median per 0.01 au data bin and their fit curves are plotted as well. The Helios data has a native distance resolution of 0.01 au, thus, to make the distribution visible in these plots, we added a random distance value of up to  $\pm 0.005$  au. The high velocity data points above  $800 \text{ km s}^{-1}$  (circled red) are identified as CME events (e.g., Sheeley et al. 1985; Bothmer & Schwenn 1996, 1998).

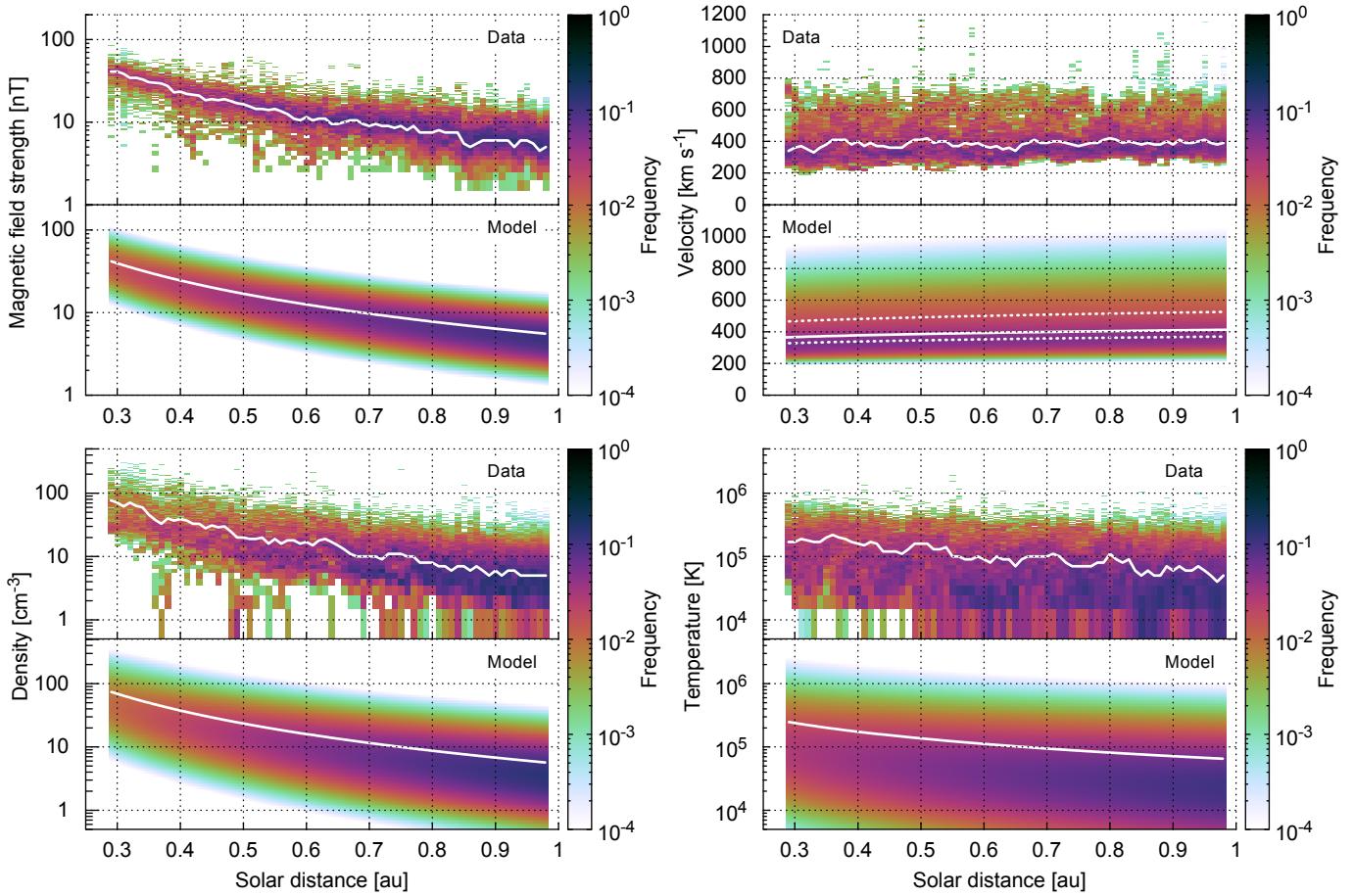
**Table 3.** Fit coefficients for the median and mean solar distance dependencies (10) of the four solar wind parameters derived from the combined Helios 1 and 2 data. The numbers in parentheses are the errors on the corresponding last digits of the quoted value. They are calculated from the estimated standard deviations of the fit parameters. The crossing distances indicate where the median and mean fits intersect each other. The yearly variation is the weighted standard deviation derived from the yearly fit exponents seen in Fig. 9.

Parameter	Median		Mean		Crossing distance [au]	Yearly variation $\Delta e$
	$d_{\text{med}}$	$e_{\text{med}}$	$d_{\text{avg}}$	$e_{\text{avg}}$		
Magnetic field [nT]	5.377(92)	-1.655(17)	6.05(10)	-1.546(18)	0.339(11)	0.11
Velocity [ $10^2 \text{ km s}^{-1}$ ]	4.107(28)	0.058(13)	4.356(24)	0.049(10)	$0.7(83) \times 10^3$	0.012
Density [ $\text{cm}^{-3}$ ]	5.61(27)	-2.093(46)	7.57(30)	-2.010(38)	0.027(73)	0.072
Temperature [ $10^4 \text{ K}$ ]	7.14(23)	-0.913(39)	9.67(21)	-0.792(28)	0.082(85)	0.050

**Table 4.** Fit coefficients for the distance-dependent single lognormal function, based on Equation (4) combined with (10) from the combined Helios data. Regarding the velocity, the double lognormal function (5) is used instead. The numbers in parentheses are the errors on the corresponding last digits of the quoted value. They are calculated from the estimated standard deviations of the fit parameters. The seasonal variations are calculated from Earth's orbital solar distance variation and the derived exponents.

Parameter	Median $d'_{\text{med}}$	Mean $d'_{\text{avg}}$	Exponent $e'$	Balance $c'$	Seasonal variation $\Delta d$ [%]
Magnetic field [nT]	5.358(25)	5.705(28)	-1.662(11)	-	2.8
Density [ $\text{cm}^{-3}$ ]	5.424(33)	6.845(47)	-2.114(20)	-	3.6
Temperature [ $10^4 \text{ K}$ ]	6.357(64)	10.72(14)	-1.100(20)	-	1.9
Velocity [ $10^2 \text{ km s}^{-1}$ ]	$W''_1$ 5.26(13)	3.748(16)	0.0990(51)	0.557(45)	0.17
	$W''_2$ $W''_{II}$ 4.13(13) <sup>a</sup>	5.42(11)	-	-	-
		4.47(11) <sup>a</sup>			

**Notes.** <sup>(a)</sup> Velocity median and mean 1 au values for the resulting function. Error estimates derived from the individual fit part errors.



**Fig. 8.** Frequency distributions of the four solar wind parameters with respect to solar distance. Plotted are the binned Helios data and the power law lognormal fit models with their median values (white lines). The double lognormal model is used for the velocity, its slow and fast parts are indicated by dotted lines.

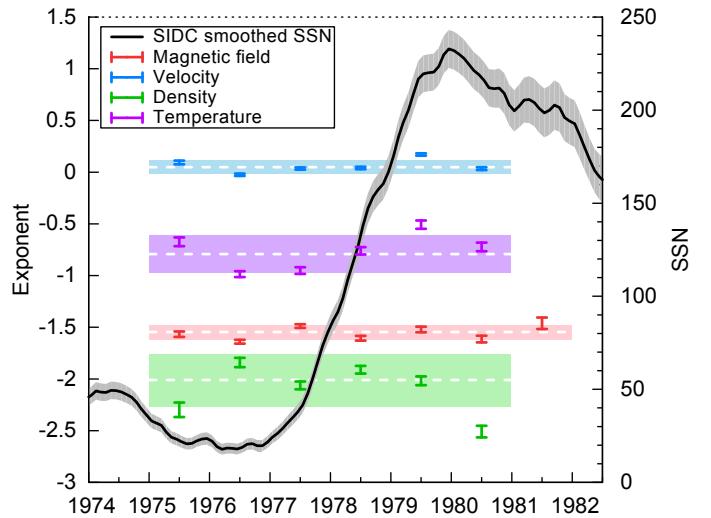
only the slowest wind but also the fastest wind is expected to converge to more average speeds (Sanchez-Diaz et al. 2016).

## 5. Empirical solar-wind model

In order to estimate the solar-wind environment for the PSP orbit, we combine the results from the solar-wind frequency distributions' solar-activity relationships and their distance dependencies derived from the OMNI and Helios data. The result is an empirical solar-wind model for the inner heliosphere which is then extrapolated to the PSP orbit in Sect. 6.

This solar-wind model for the radial distance dependence is representative for the time of the Helios observations around the rise of solar cycle 21. The variations of the yearly power law fit exponents from fitting the solar-distance dependency (10) are shown in Fig. 9 together with the yearly SSN for the time period 1974–1982. It can be seen that during the Helios time period there might be some systematic variation of the exponents with solar activity – at least for the velocity and temperature exponents. However, for simplicity we assume that the distance scaling laws can be treated as time independent and include the calculated exponents' yearly variations  $\Delta e$ , summarized in Table 3, as relative uncertainties.

Since we neglect possible variations of the distance scaling laws, we combine the frequency distribution's median solar activity dependency (7) derived for 1 au from the OMNI data with



**Fig. 9.** Helios yearly variation of the solar wind parameter power exponents for the dependence on radial distance together with the SIDC 13-month smoothed monthly SSN. The weighted standard deviations and average values for all years are indicated by the shaded areas. In this plot, the 21 days since Helios launch in the year 1974 are omitted because a distance range of merely 0.95–0.98 au was covered that year.

the power law exponents (10) derived from the Helios data:

$$x_{\text{med}}(ssn, r) = (a_{\text{med}} \cdot ssn + b_{\text{med}}) \cdot r^{e'}. \quad (11)$$

Thus, implementing the median and mean relations into the log-normal function (4), we obtain the combined model function  $W'''(x, ssn, r)$  and for the velocity  $W''_{II}(x, ssn, r)$  with the double lognormal function (5). The corresponding median and mean relations for each solar-wind parameter, based on the values resulting from our analyses, are listed below. Their numerical values are the fit parameters from Table 2 and the exponents from Table 4.

- The magnetic field strength relations, depending on solar activity and solar distance, are:

$$B_{\text{med}}(ssn, r) = (0.0131 \text{ nT} \cdot ssn + 4.29 \text{ nT}) \cdot r^{-1.66}, \quad (12)$$

$$B_{\text{avg}}(ssn, r) = 1.0879 \cdot B_{\text{med}}(ssn, r). \quad (13)$$

- The proton velocity relations for the slow and fast components, depending on solar distance, are:

$$v_{\text{med}}^{\text{slow}}(r) = 363 \text{ km s}^{-1} \cdot r^{0.099}, \quad v_{\text{med}}^{\text{fast}}(r) = 483 \text{ km s}^{-1} \cdot r^{0.099}, \quad (14)$$

$$v_{\text{avg}}^{\text{slow}}(r) = 1.0101 \cdot v_{\text{med}}^{\text{slow}}(r), \quad v_{\text{avg}}^{\text{fast}}(r) = 1.023 \cdot v_{\text{med}}^{\text{fast}}(r). \quad (15)$$

The share of both components balanced with solar activity is found to be:

$$c(ssn) = -0.00180 \cdot ssn + 0.64. \quad (16)$$

- The derived relations of the proton density are:

$$n_{\text{med}}(ssn, r) = (0.0038 \text{ cm}^{-3} \cdot ssn + 4.50 \text{ cm}^{-3}) \cdot r^{-2.11}, \quad (17)$$

$$n_{\text{avg}}(ssn, r) = 1.305 \cdot n_{\text{med}}(ssn, r). \quad (18)$$

- The derived proton temperature relations are:

$$T_{\text{med}}(ssn, r) = (197 \text{ K} \cdot ssn + 57\,300 \text{ K}) \cdot r^{-1.10}, \quad (19)$$

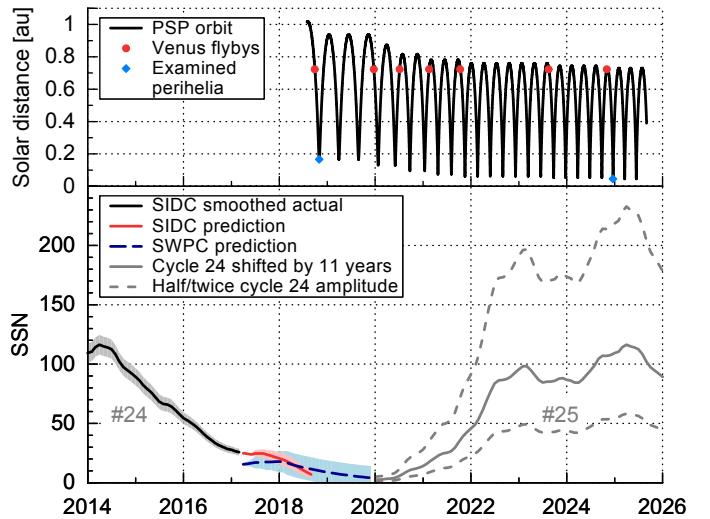
$$T_{\text{avg}}(ssn, r) = 1.654 \cdot T_{\text{med}}(ssn, r). \quad (20)$$

These relations average over seasonal variations because they are based on yearly data. The OMNI data are time-shifted to the nose of the Earth's bow shock; this leads to yearly solar distance variations of  $\pm 1.67\%$  as it orbits the Sun. The resulting maximal solar-wind parameter variation amplitudes over the year can thus be derived from the derived power law exponents. They are estimated to be smaller than 4 % as seen in Table 4. Bruno et al. (1986) and Balogh et al. (1999) have pointed out that the solar-wind parameters vary with latitudinal separation from the heliospheric current sheet. Its position in heliographic latitude is highly variable around the solar equator (Schwenn 1990) and, furthermore, the Earth's orbit varies over the course of the year by  $\pm 7.2^\circ$  in latitude. Since this latitudinal separation is highly variable and requires significant effort to calculate for an extended time series, we have ignored this aspect in this analysis.

## 6. Model extrapolation to PSP orbit

To estimate PSP's solar-wind environment during its mission time for its orbital positions, predictions of the SSN during the mission are incorporated into the empirical solar-wind model, derived in the previous Sections, and extrapolations down to the PSP perihelion region are performed.

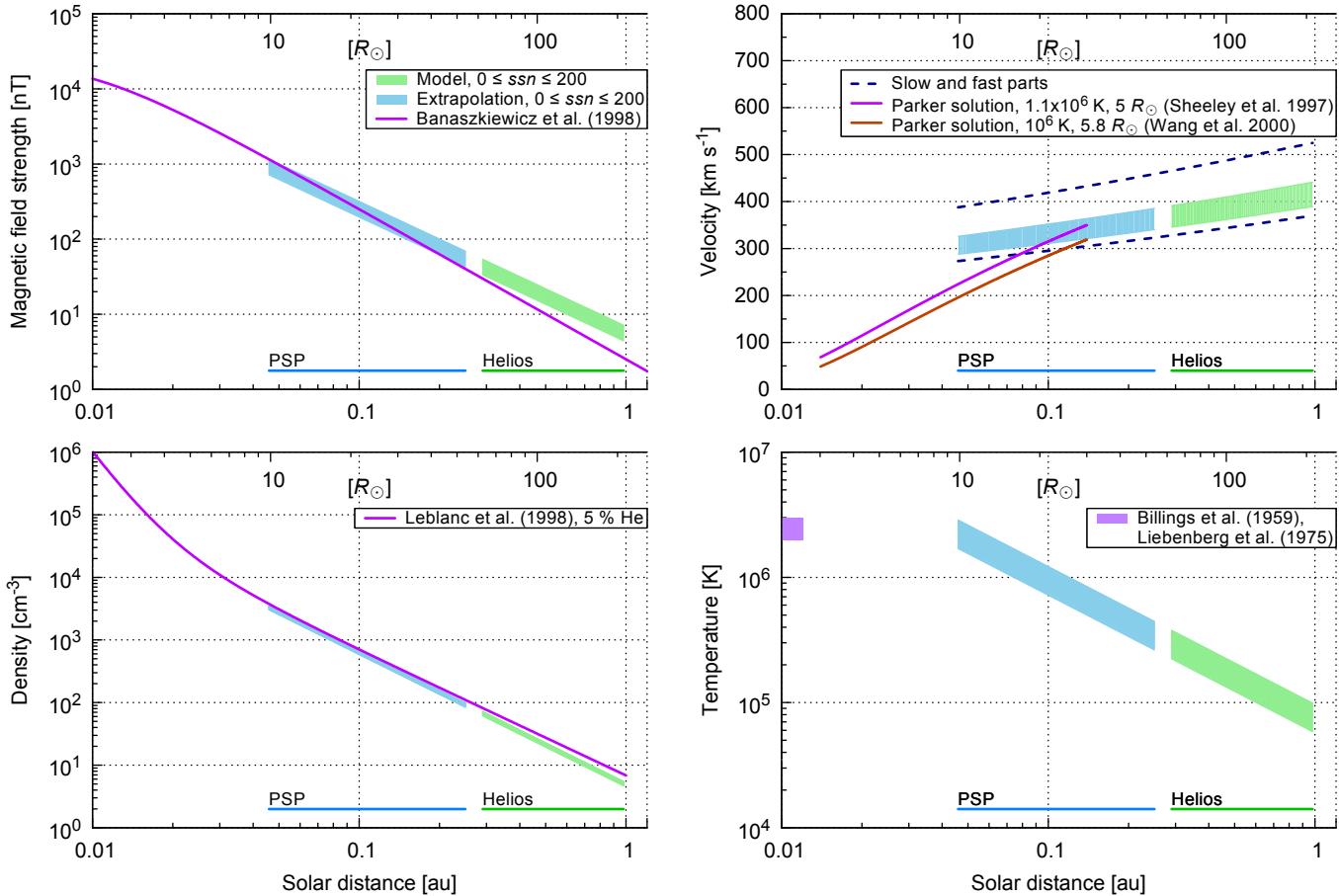
Parker Solar Probe is planned to launch in mid 2018. With its first Venus flyby it will swing into Venus' orbital plane, reaching a first perihelion with a distance of 0.16 au just 93 days after



**Fig. 10.** PSP's solar distance during its mission time (top). Consecutive Venus flybys bring its perihelia nearer to the Sun. Actual and predicted SSN (bottom), that is, SIDC 13-month smoothed monthly actual SSN, SIDC Standard Curves Kalman filter prediction and SWPC prediction with their corresponding expected ranges (shaded areas). The SSN from previous cycle 24, shifted by 11 years, is plotted together with two alternative trends of half and twice its amplitude.

launch, in November 2018. Seven additional Venus flybys allow the perihelion distance to be reduced to a minimum of  $0.16 \text{ au}$ . This distance will be reached with the 22nd perihelion in December 2024 (Fox et al. 2015), as plotted in the top panel of Fig. 10.

We extrapolate the derived empirical solar-wind models to PSP's orbital distance range and compare the results with those from the existing models shown in Fig. 11. The model and its extrapolation are visualized for the SSN range between solar minimum and maximum ( $0 \leq ssn \leq 200$ ), indicated by the shaded regions in the Figure. The magnetic field strength is found to increase from median values of about 43 nT at 0.25 au to 715 nT at 0.046 au for a SSN of zero. Taking a SSN of 200 increases the values to 69 nT and 1152 nT. Our extrapolation results are slightly flatter than those derived from the analytical magnetic field model by Banaszkiewicz et al. (1998), who constructed an analytic dipole plus quadrupole plus current sheet (DQCS) model for solar minimum. We note that one cannot easily compare the absolute values of our study with the values obtained by Banaszkiewicz et al. (1998) because the DQCS model assumes solar wind originating from coronal holes at higher heliographic latitudes only, neglecting the slow solar-wind belt. We suggest that the difference in slope is due to the previously mentioned (Sect. 4) changing shape of the frequency distribution with heliocentric distance, which for smaller distances deviates more from the model's lognormal distribution. The average velocity is found to decrease from  $340 \text{ km s}^{-1}$  at 0.25 au to about  $290 \text{ km s}^{-1}$  at 0.046 au 3 years after a SSN of zero occurred, whereas using a SSN of 200 it decreases from  $390 \text{ km s}^{-1}$  to  $330 \text{ km s}^{-1}$ . Comparing the results with the measurements by Sheeley et al. (1997) and Wang et al. (2000) shows an overestimation in our extrapolated slow solar-wind velocity values for distances below approximately  $20 \text{ R}_\odot$ . They used LASCO coronagraph observations to track moving coronal features (blobs) in the distance range  $2\text{--}30 \text{ R}_\odot$  to determine speed profiles and sources of the slow solar wind and they derived temperature and sonic point values for slow solar wind with the isothermal expansion model from Parker (1958). Therefore, it generally can be expected that



**Fig. 11.** Radial extrapolation of the solar-wind parameters to the PSP orbit region. The median values from the models, obtained from Helios and OMNI measurements, are extrapolated to the PSP region for SSN values between solar minimum and maximum, that is,  $0 \leq \text{ssn} \leq 200$ . The lower edges of the shaded areas correspond to solar minimum, the upper edges to solar maximum. Also plotted are the radial dependencies of the analytic DQCS magnetic field model for solar minimum from Banaszkiewicz et al. (1998), the slow wind velocity models from Sheeley et al. (1997) and Wang et al. (2000), the density model from Leblanc et al. (1998) and the range of temperature measurements from Billings (1959) and Liebenberg et al. (1975).

PSP will encounter a slower solar-wind environment close to the Sun than our model estimates. Thus PSP will measure solar-wind acceleration processes (McComas et al. 2008), maybe even still at  $30 R_{\odot}$  as the study by Sheeley et al. (1997) suggests. The proton density increases from about  $84 \text{ cm}^{-3}$  at 0.25 au to about  $3018 \text{ cm}^{-3}$  at 0.046 au 6 years after a SSN of zero occurred. Being almost independent of the SSN, the values for a SSN of 200 are only 17 % larger. The results are in good agreement with those of Leblanc et al. (1998), who derived an electron density model from type III radio burst observations. Their model shows that the density distance dependency scales with  $r^{-2}$  and steepens just below  $10 R_{\odot}$  with  $r^{-6}$ . We assumed a solar-wind helium abundance of 5 % to convert these electron densities to proton densities. The extrapolated proton temperature increases from about 260 000 K at 0.25 au to about 1 690 000 K at 0.046 au 3 years after a SSN of zero occurred and from 440 000 K to 2 860 000 K for a SSN of 200. Knowing that near-Sun coronal temperatures are in the range of 2–3 MK (Billings 1959; Liebenberg et al. 1975), the model overestimates the extrapolated temperatures at the PSP perihelion distance.

Aside from the solar distance, the derived solar-wind parameter models depend on the SSN. Short-term predictions of the SSN can be used for the solar-wind predictions of PSP's early perihelia and also for refining the solar-wind predictions during PSP's mission. Several sources are available for SSN

short-term predictions. The SIDC provides 12-month SSN forecasts<sup>6</sup> obtained from different methods (e.g., Kalman filter Standard Curve method). The SSN prediction of NOAA's Space Weather Prediction Center (SWPC) for the time period until the end of 2019 follows a consensus of the Solar Cycle 24 Prediction Panel<sup>7</sup>. The SSN for PSP's first perihelion will be small – certainly below 20 – whereas the SSN during the closest perihelia, which will commence at the end of 2024 at the likely maximum phase of cycle 25, cannot be predicted at this time. However, Hathaway & Upton (2016) found indications that the next solar cycle will be similar in size to the current cycle 24. Therefore we simply assume a pattern similar to the last cycle for the prediction of the next solar cycle and thus shift the last cycle by 11 years. Additionally, we consider as possible alternatives SSN patterns of half and twice its amplitude as shown in the bottom panel of Fig. 10.

Implementing the SSN predictions for the PSP mission time and the orbital trajectory data, we can infer which solar-wind parameter magnitudes can be expected. Figures 12 and 13 show the median values (7) of the considered different solar-wind parameters for 12-day periods, comprising the first perihelion in

<sup>6</sup> <http://sidc.be/silso/forecasts>

<sup>7</sup> <http://www.swpc.noaa.gov/products/solar-cycle-progression>



**Fig. 12.** Estimated solar-wind parameter medians (black lines) and their error bands (gray) during 12 days in 2018 with PSP's first perihelion at about 0.16 au. For the velocity the combined median is calculated and also the SSN-independent slow and fast parts are plotted (dotted lines).



**Fig. 13.** Estimated solar-wind parameter medians (black lines) and their error bands (gray) during 12 days in December 2024 with PSP's 22nd (the first closest) perihelion at 0.0459 au. For the velocity the combined median is calculated and also the SSN-independent slow and fast parts are plotted (dotted lines).

November 2018 and the first closest perihelion in December 2024. In the beginning of the mission median values of about 87 nT, 340 km s<sup>-1</sup>, 214 cm<sup>-3</sup> and 503 000 K are estimated to be measured at 0.16 au, increasing to about 943 nT, 290 km s<sup>-1</sup>, 2951 cm<sup>-3</sup> and 1 930 000 K during the first closest approach at 0.046 au. Monthly SSNs – shifted by the time lags specific to the solar-wind parameters – are used in the calculation of the solar-wind predictions. These SSNs are either actual smoothed values from the SIDC with their reported standard deviations, short-term predictions from the SWPC with their expected ranges, or actual smoothed values from the SIDC shifted by 11 years with half/twice their values as uncertainties. The error bands given in both Figures, calculated from error propagation, include these SSN ranges and the derived fit parameter errors.

Finally the estimated solar-wind environment can be derived from the function  $W'''(x, ssn, r)$ . The estimated frequency distributions of the four solar-wind parameters at PSP's 1st and 22nd



**Fig. 14.** Frequency distributions of the four solar-wind parameters (same as in Figs. 1 and 2) and those estimated with the solar-wind model for PSP's 1st and 22nd (first closest) perihelion. In these Figures the frequencies of both extrapolated curves are scaled for visibility to the same height as the 1 au distribution.

(first closest) perihelion are plotted in Fig. 14. Again, we point out that the velocity and temperature distributions for the 22nd perihelion are only upper limits and the actual values to be encountered by PSP are expected to be smaller.

## 7. Discussion and summary

The scientific objective of this study, being part of the CGAUSS project – the German contribution to the WISPR instrument – is to model the solar-wind environment for the PSP mission to be launched mid 2018. For this purpose we started the development of the empirical solar-wind environment model for the near-ecliptic PSP orbit. We derived lognormal representations of the in situ near-Earth solar-wind data collected in the OMNI database, using the frequency distributions of the key solar-wind parameters, magnetic field strength, proton velocity, density, and temperature. Throughout the different analyses in our study, the velocity's frequency distribution is treated as a composition of a slow and a fast wind distribution. Each velocity part is fitted with a lognormal function, which allows for the overlap of both velocity ranges. The OMNI multi-spacecraft solar-wind data is intercalibrated and covers almost five solar cycles. It thus represents solar wind gathered at different phases of solar activity in the ecliptic plane. In the next step we investigated the yearly variation of the solar-wind distribution functions along with the SSN over 53 years and derived linear dependencies of the solar-wind parameters with the SSN. The radial dependencies of the solar-wind distribution functions were then analyzed, using Helios 1 and 2 data for the distance range 0.29–0.98 au in bins of 0.01 au, deriving power law fit functions that were used to scale the previously calculated SSN-dependent 1 au distribution fit functions to the PSP orbit, taking into account SSN predictions for the years 2018–2025, encompassing the prime mission up to the closest approach of 9.86 R<sub>⊕</sub>. The reason for performing the analysis this way is based on the fact that the OMNI solar-wind database is much larger than the Helios database.

For determining solar-activity- and solar-distance-dependent relations for the median and mean solar-wind values, we could have used the simpler approach of combining the radial depen-

dence of averaged Helios data with averaged 1 au OMNI data scaled with the SSN. It is expected that the results of a simpler analysis would have similar distance scaling results, as can be inferred from the exponents in Tables 3 and 4. However, in our study we are not only interested in averages but rather in bulk distributions, that is, the whole range of values that might occur. For the determination of the frequency distributions the use of the more complex fit model is important, because the distance between median and mean values determines the width of the lognormal distributions.

It is clear that the calculated distribution functions only represent first-order estimates of the real solar wind to be encountered by PSP. The solar-wind environment to be encountered will depend at times of PSP on the structure of the solar corona and underlying photospheric magnetic field and on the evolution and interaction of individual solar-wind streams and superimposed CMEs and shocks. However, the derived results are in good agreement with existing studies about near-Sun solar-wind magnetic field strengths and densities as shown in Sect. 6. The extrapolation results of the velocity and the temperature differ from the direct measurements seen in existing studies. This suggests that below about  $20 R_{\odot}$  PSP may dive into the region where the acceleration and heating of the solar wind is expected to occur (see Fig. 11). The near-Sun solar-wind velocity at PSP perihelion is also expected to be slower than our model estimates, because the solar wind is assumed to be accelerated up to the height of the Alfvénic critical surface, which is predicted to lie on average around  $17 R_{\odot}$  (e.g., Sittler & Guhathakurta 1999; Exarhos & Moussas 2000), scaling with solar activity within a range of between  $15 R_{\odot}$  at solar minimum and  $30 R_{\odot}$  at solar maximum (Katsikas et al. 2010; Goelzer et al. 2014).

We have not specifically investigated the occurrences of extreme solar-wind parameters caused by CMEs or enhanced values due to stream interaction or co-rotating interaction regions. The Helios solar-wind measurements plotted over radial distance in Fig. 7 show several extreme values far above the usual solar-wind velocities, which are associated with individual CMEs. The results by Sachdeva et al. (2017) indicate that due to solar-wind drag, the speeds of fast CMEs will commonly slow down substantially from early distances of a few solar radii. Therefore, it is expected that PSP will encounter CMEs with much higher speeds than those observed during the Helios mission. Also, the magnetic field, density and temperature values are expected to be much larger than in the average solar wind in individual fast-shock-associated CME events. PSP will thus also substantially improve our understanding of the near-Sun evolution of CMEs and their expansion with radial distance.

With the resulting CGAUSS empirical solar-wind model for PSP, the following main results for the bulk solar-wind parameters and estimations for their median values at PSP's first perihelion in 2018 at a solar distance of 0.16 au and at PSP's closest perihelia beginning in 2024 at 0.046 au ( $9.86 R_{\odot}$ ) are obtained:

- The dependency of the magnetic field strength on solar activity and radial distance appears to be valid above  $20 R_{\odot}$ , however near PSP's closest perihelia, the actual values might be found to be slightly higher.
- The estimated magnetic field strength median values obtained from relation (12) for PSP's 1st and 22nd perihelion are  $87 \text{ nT}$  and  $943 \text{ nT}$ .
- The radial dependencies of the proton velocity median values for slow and fast solar wind (14) appear to be valid above about  $20 R_{\odot}$  solar distance; below they overestimate the actual solar wind velocities obtained from remote measurements. The share of their frequency distributions to the

overall solar-wind velocity distribution (5) depends on solar activity with their balance relation (16). Thus, at solar minimum, with a SSN of around zero, the slow-wind component contributes about 64 % and drops to 28 % during solar maximum conditions with a SSN around 200.

- The calculated median velocity values for PSP's 1st and 22nd perihelion are  $340 \text{ km s}^{-1}$  and  $290 \text{ km s}^{-1}$ .
- The proton density relation appears to be valid throughout the full PSP orbital distance range, even down to about  $8 R_{\odot}$ .
- The estimated density median values obtained from relation (17) for PSP's 1st and 22nd perihelion are  $214 \text{ cm}^{-3}$  and  $2951 \text{ cm}^{-3}$ .
- The derived correlation function for the proton temperature appears to provide overly high temperature values around PSP's closest perihelion in comparison to coronal measurements.
- The estimated temperature median values obtained from relation (19) for PSP's 1st and 22nd perihelion are  $503\,000 \text{ K}$  and  $1\,930\,000 \text{ K}$ .

The results of the modeled solar-wind environment will be useful to help optimize the WISPR and in situ instrument science plannings and PSP mission operations. This also applies for the Heliospheric Imager (SoloHI) (Howard et al. 2013) and the in situ instruments on board the Solar Orbiter spacecraft.

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## 7 Summary, conclusions, and outlook

### 7.1 Summary and conclusions

already in chapters:

results

discussion

conclusions

end matter:

summary

outlook

I built an empirical solar wind model for the ecliptical inner heliosphere which accounts for variations in time (season and solar cycle) and space (solar distance).

Prediction:

Long-term solar wind parameter predictions from SSN

Link from near-Sun solar wind measurements to K<sub>p</sub> impact

Link from near-Sun structure (CMEs, CIRs) measurements to K<sub>p</sub> impact

### 7.2 Outlook

Outlook

DSCOVR data (advantages over ACE? gain?)

anticipated Parker Solar Probe data (near-Sun data)

other possible space weather missions: sub-L1 (earlier in-situ CME magnitude warning) and L5 (early CME velocity and arrival warning)

SPP orbit: 1.09 SPP orbit presentation-Lario.ppt

Using the SSN prediction, the derived solar wind model allows the forecast and extrapolation of the solar wind environment, occurring during the PSP mission's near-Sun encounters from end of 2018 on.



# A Appendix

## A.1 Solar surface differential rotation

The solar differential rotation is visible on the surface and was first discovered from sunspot observations by Scheiner (1630). (double)

Bartels (1934) set the synodic solar rotation period to 27 days for the definition of his solar rotation number. The Bartels' Rotation Number counts the solar rotations starting with 8 February 1832.

Carrington solar rotation period of 27.2753 days (Where Carrington Rotation Number is based upon, starting with November 9, 1853; Wikipedia...)

Solar surface rotation period at 16° latitude:  
sidereal: 25.38 d (of 609.12 h Sun Fact Sheet...), synodic: 27.2753 d (derived)

rotation axis tilt (see next section)

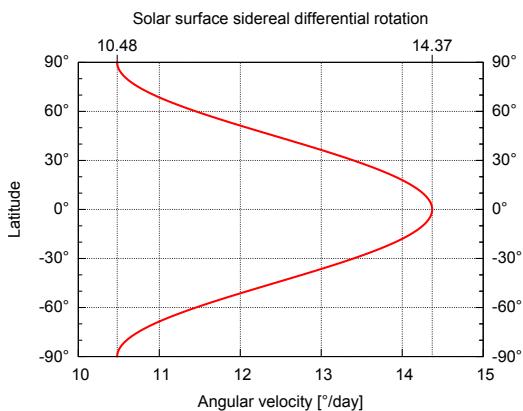
The Sun's inner thermal convective circulation results in a differential rotation caused by transport of angular momentum away from the rotation axis.

The Sun's sidereal differential angular velocity best-fitting function with values as stated in (Sun Fact Sheet...)<sup>1</sup> is

$$\omega_{\odot}(\theta) = \omega_{\text{eq}} + B \sin^2(\theta) + C \sin^4(\theta) \quad (\text{A.1})$$

with the heliolatitude  $\theta$ , the equatorial angular velocity  $\omega_{\text{eq}} = 14.37^\circ \text{d}^{-1}$ , the coefficients  $B = -2.33^\circ \text{d}^{-1}$ , and  $C = -1.56^\circ \text{d}^{-1}$  (see Figure A.1).

see Figure A.1



**Figure A.1** Diagram of the sidereal solar surface differential rotation. It shows the angular velocity for different latitudes. remove sides...

Thus, the solar equatorial rotation period (sidereal) is

$$\begin{aligned} T_{\odot}^{\text{eq}} &= 360^\circ / A \\ &= 25.05 \text{ d} \end{aligned} \quad (\text{A.2})$$

and the synodic period is

$$\begin{aligned} T_{\odot}^{\text{eq,syn}} &= 1 / (1/T_{\odot}^{\text{eq}} - 1/T_{\text{Earth}}) \\ &= 26.90 \text{ d} \end{aligned} \quad (\text{A.3})$$

with the Earth's orbital rotation period  $T_{\text{Earth}} = 365.25 \text{ d}$  (1/100 Julian century).

<sup>1</sup>NASA's Sun Fact Sheet (<http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html>, accessed 2016-08-19).

Solar surface rotation period at equator  
sidereal: 25.05 d (Sun Fact Sheet...), synodic: 26.90 d (derived)  
Solar surface rotation period at poles:  
sidereal: 34.35 d (diff. rot. formula), synodic: 37.92 d (derived)  
are listed in [Table A.1](#).

**Table A.1** Solar surface rotation periods for equator,  $\pm 16^\circ$  latitude and poles (sidereal and synodic).

	Equator [d]	$\pm 16^\circ$ latitude [d]	Poles [d]
Sidereal	25.05	25.38	34.35
Synodic	26.90	27.2753 <sup>a</sup>	37.92

<sup>a</sup>Carrington solar rotation period

The meridional circulation is the proposed equatorial updrift and polar downdrift - a result of Reynolds stress and convective transport ([cite?](#)).

## A.2 Plasma beta

The thermal pressure of a plasma is defined as  $p = nk_B T$ , with the number density  $n$  and the Boltzmann constant  $k_B$ . However, according to magnetohydrodynamics (MHD), the magnetic energy density  $w_{\text{mag}} = \frac{B^2}{2\mu_0}$ , with the magnetic field strength  $B$  and the permeability constant  $\mu_0$ , behaves like an additional pressure that adds to the thermal pressure of a plasma ([Kivelson & Russell 1995](#), p. 50). The ratio of the thermal pressure to the magnetic pressure determines the behavior of the plasma. If the thermal pressure dominates the magnetic pressure (warm plasma), the plasma movements transport the magnetic field else the plasma movements are guided by the magnetic field lines (cold plasma). This ratio is called plasma beta:

$$\beta = \frac{p}{p_{\text{mag}}} , \quad (\text{A.4})$$

$$= \frac{2\mu_0 n k_B T}{B^2} . \quad (\text{A.5})$$

The plasma at the photosphere has typical beta values around 14 and that of the low corona around 0.2 ([Gary 2001](#)). Further up, beta raises again and the region where it equals 1 is defined as the source surface for the solar wind ([Schatten et al. 1969](#)). This surface is typically located at about  $1.2\text{--}2.5 R_\odot$  ([Gary 2001](#)), more cites...

The solar wind usually has plasma beta values higher than 1 – it carries the solar magnetic field away into the heliosphere. Together with the solar rotation, this effect creates the spiral form of the interplanetary magnetic field (Parker spiral). Yet in some solar wind structures, such as magnetic clouds,  $\beta \ll 1$  and thus the magnetic field can still contain the plasma.

## A.3 Alfvén velocity

The incompressible wave mode within MHD plasmas, the shear Alfvén wave, consists of periodic disturbances in the magnetic field orthogonal to its direction ([Alfvén 1942](#)). Alfvén waves are prevalent in open coronal regions and therefore occur in fast solar wind ([Cranmer & van Ballegooijen 2005](#)). Their propagation velocity is an important parameter to characterize a plasma. In an ideal incompressible MHD plasma (viscosity  $\mu = 0$  and electrical conductivity  $\sigma = \infty$ ) the kinetic and magnetic energy density are of equal value ([Kivelson & Russell 1995](#), p. 51):

$$w_{\text{kin}} = w_{\text{mag}} \quad (\text{A.6})$$

$$\frac{\rho v^2}{2} = \frac{B^2}{2\mu_0}$$

with the permeability constant  $\mu_0$  and the total mass density  $\rho$  of the charged plasma particles. Thus, the Alfvén velocity can be calculated from

$$v_A = \frac{|B|}{\sqrt{\mu_0 \rho}}. \quad (\text{A.7})$$

The wave's phase velocity is

$$v_{\text{ph}} = v_A \cos(\theta) \quad (\text{A.8})$$

with  $\theta$  as the angle between wave propagation direction and magnetic field line, that is, Alfvén waves travel along magnetic field lines. They consist of periodic disturbances in the magnetic field, the electric field, the plasma velocity, and the current density. Plasma density, pressure and magnetic field magnitude are not affected by them. Additionally, there exist two types of compressional wave modes within MHD plasmas, the fast-mode wave and the slow-mode wave. The phase speeds of the three MHD waves meet  $v_{\text{fast}} \geq v_A \geq v_{\text{slow}}$  (Kivelson & Russell 1995, p. 52). Within solar wind at 1 au, the typical frequency of Alfvén waves is 1–4 per hour and their average velocity is  $v_A = 56.8 \text{ km s}^{-1}$  (Veselovsky et al. 2010).

Alfvén critical surface...  
sonic critical surfaces...

## A.4 Sun-Earth orbit geometry

orbit defines ecliptic

Earth orbit parameters (cite?):  
semimajor axis:  $a = 1.000001018 \text{ au}$   
eccentricity:  $e = 0.0167086 \text{ au}$   
distance at perihelion: (formula cite?, accuracy?)

$$\begin{aligned} r_p &= a(1 - e) \\ &= 0.98329 \text{ au} \end{aligned} \quad (\text{A.9})$$

distance at aphelion:

$$\begin{aligned} r_p &= a(1 + e) \\ &= 1.0167 \text{ au} \end{aligned} \quad (\text{A.10})$$

for calculation of heliospheric distance see HORIZONS Web-Interface at <http://ssd.jpl.nasa.gov/horizons.cgi>

perihelion/aphelion times...

### Solar distance

Sun-Earth distance over the course of the year.

In the year 2017 Earth's perihelion was on 5 January with a distance of  $-1.67\%$  from 1 au (Horizons On-Line Ephemeris System<sup>2</sup>, Solar System Dynamics Group, Jet Propulsion Laboratory).

The cosine approximation

$$r_E(t) = 1 - 0.0167 \cdot \cos\left(2\pi\left(t - 2017 - \frac{5}{365}\right)\right), \quad (\text{A.11})$$

with  $t$  in years, suffices for our accuracy requirements.

seasonal variation function:  
 $X_{\text{avg}}(t) = a r_E(t)^b$

---

<sup>2</sup><http://ssd.jpl.nasa.gov/horizons.cgi>

## Solar rotation axis tilt to the ecliptic

The inclination of the solar equator to the ecliptic (tilt/obliquity) is  $i_{\odot} = 7.25^\circ$  ([U.S. Nautical Almanac Office 2015](#)).

the rotation axis is tilted from the ecliptic normal

Viewed from Earth the projected solar rotation axis tilt angle varies as the Earth is moving on its orbit.

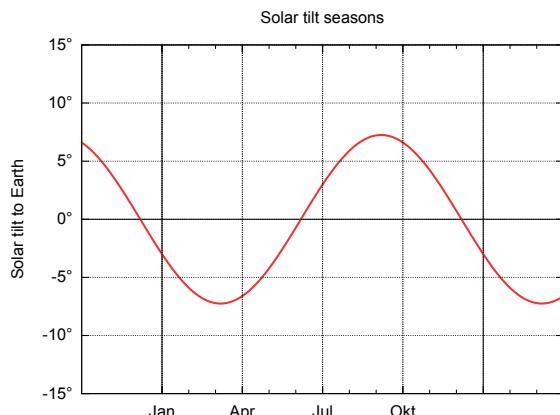
At the time XX the angle is zero.

The projected tilt angle to Earth over the year is

[Hapgood \(1992\)](#):

$$\omega = 73.67 + 0.013\,958 * (\text{today} - 1850.0) \quad (\text{A.12})$$

solar tilt over the year, see [Figure A.2](#)



**Figure A.2** Projected solar tilt angle over the year as viewed from Earth. remove sides...

## Earth rotation axis tilt to the ecliptic

### A.5 Coordinate systems

Coordinate systems used in this thesis:

GSE - Geocentric Solar Ecliptic

GSM - Geocentric Solar Magnetospheric

HGI - Heliographic Inertial

refer to [Hapgood \(1992\)](#) for GSE and GSM

figures for GSE and GSM

### Geocentric Solar Ecliptic

The Geocentric Solar Ecliptic (GSE) coordinates are

GSE - Geocentric Solar Ecliptic

X = Earth-Sun Line

Z = Ecliptic North Pole

GSE coordinates are used in ACE solar wind data, etc.

see Jursa1985, p. 4-3

“the polar axis is the axis inclined  $11.5^\circ$  to the axis of rotation, intersecting the earth surface at the point  $78.5^\circ\text{N}$ ,  $291.0^\circ\text{E}$  which defines the geomagnetic north pole. This was once at one time the axis of the best centered-dipole approximation to the field”

## Geocentric Solar Magnetospheric

GSM - Geocentric Solar Magnetospheric  
X = Earth-Sun Line  
Z = Projection of dipole axis on GSE YZ plane

GSM is defined with a time dependent dipole axis.  
the dipole axis orientation changes over time; at 1995 the northern pole was at  $l = 288.59^\circ$  and  $b = 79.30^\circ$ ;  
more recent year (2015)?... cite?

## Heliographic Inertial

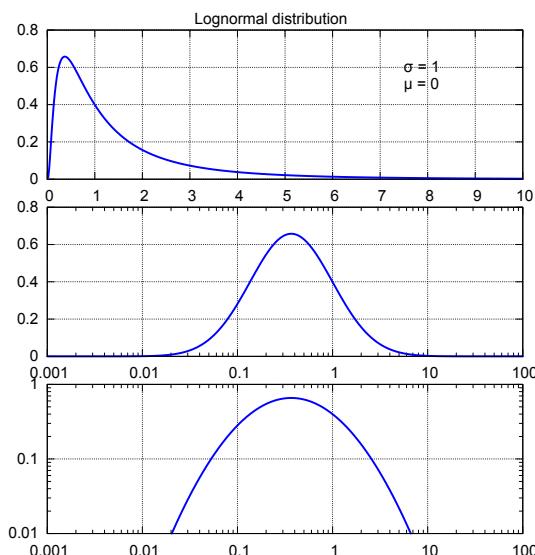
Heliographic Inertial (HGI) coordinates

HGI coordinates are Sun-centered with the z-axis directed along the solar rotation axis and directed northward of the solar equator. The solar equator plane is inclined  $7.25^\circ$  from the ecliptic.

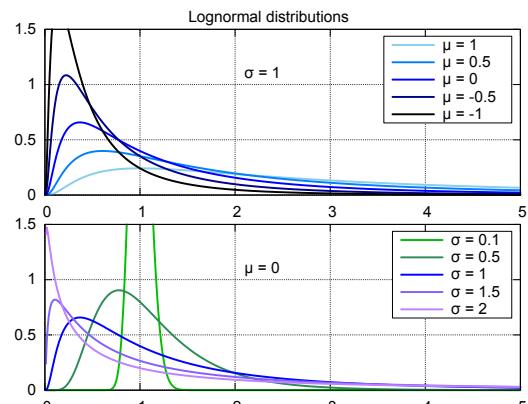
HGI coordinates; latitude range  $-7.25^\circ$  to  $-7.25^\circ$   
latitude variation (see Schwenn1990, p. 127)

## A.6 Lognormal distribution

This is a small summary about the lognormal probability distribution (Bronstein et al. 2000, p. 780). The lognormal distribution is the distribution of a random variable  $X$  if the logarithm of  $X$  conforms to a normal distribution. Its shape is highly asymmetric, however in a semi-log plot the Gaussian bell curve is recognizable (see the second panel of Figure A.3). Its probability density function is



**Figure A.3** The lognormal probability density function ( $\sigma = 1, \mu = 0$ ) plotted in a linear, semi-log and log-log way. remove borders...



**Figure A.4** Five lognormal distributions plotted with fixed  $\sigma$  (top) and fixed  $\mu$  (bottom). remove borders...

$$f(x) = \frac{1}{\sigma \sqrt{2\pi}x} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} \quad (\text{A.13})$$

with the location ( $\mu$ ) and the shape parameter ( $\sigma$ ). Changes in  $\mu$  affect both the horizontal and vertical scaling of the function, whereas  $\sigma$  has an influence on its shape (see Figure A.4).

## A. Appendix

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Because it is a probability distribution, its area is normalized

$$\int_0^\infty f(x)dx = 1. \quad (\text{A.14})$$

For a lognormally distributed random variable the geometric moments mean, standard deviation and variance are:

$$\begin{aligned}\mu_g &= e^\mu, \\ \sigma_g &= e^\sigma, \\ var_g &= e^{\sigma^2} \quad (!).\end{aligned}$$

Its arithmetic moments are:

$$\begin{aligned}\mu_a &= e^{\mu + \frac{\sigma^2}{2}}, \\ \sigma_a &= e^{\mu + \frac{\sigma^2}{2}} (e^{\sigma^2} - 1), \\ var_a &= \sigma_a^2.\end{aligned}$$

Other useful characteristics are the median and the mode

$$\begin{aligned}x_{\text{median}} &= e^\mu, \\ x_{\text{mode}} &= e^{\mu - \sigma^2}.\end{aligned}$$

Note that for the lognormal distribution its median is equal to its geometric mean.

Applications of lognormal distributions...

Most natural quantities which can only be positive are lognormally distributed. e.g. animal body sizes?, animal life expectancies, financial stock prices...; income distributions.

## A.7 Astronomical constants

Astronomical unit: 1 au = 149 597 870 700 m ([U.S. Nautical Almanac Office 2015](#))

Solar mass:  $M_\odot = 1.9884(2) \times 10^{30}$  kg ([U.S. Nautical Almanac Office 2015](#))

Nominal solar radius (photosphere):  $R_\odot = 695 700$  km ([Mamajek et al. 2015](#))

Solar rotation axis tilt:  $i_\odot = 7.25^\circ$  ([U.S. Nautical Almanac Office 2015](#))

Solar surface rotation period at equator, sidereal: 25.05 d ([Sun Fact Sheet...](#))

Nominal solar effective temperature (photosphere):  $T_{\text{eff}\odot} = 5772$  K ([Mamajek et al. 2015](#))

Sun escape velocity:  $v_{\text{esc}} = 617.6$  km/s ([Sun Fact Sheet...](#))

NASA maintains the Planetary Fact Sheets<sup>3</sup> online.

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<sup>3</sup>NASA Planetary Fact Sheets website: <https://nssdc.gsfc.nasa.gov/planetary/planetfact.html>

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We would like to thank XX for reading drafts of this manuscript...

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The results presented in this thesis rely on the *Kp* index, calculated and made available by the German Research Centre for Geosciences in Potsdam from data collected at magnetic observatories. We thank the involved national institutes, the INTERMAGNET network and ISGI (isgi.unistra.fr).

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Data acknowledgments for [Chapter 4](#):

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## References

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Programme (FP7/2007-2013) under the grant agreement number 263506 (AFFECTS). The results presented in this paper rely on the  $K_p$  index, calculated and made available by the German Research Centre for Geosciences in Potsdam from data collected at magnetic observatories. We thank the involved national institutes, the INTERMAGNET network and ISGI ([isgi.unistra.fr](http://isgi.unistra.fr)). The authors thank the OMNI PIs/teams for creating and making available the solar-wind in-situ data. The OMNI data are supplied by the NASA Space Science Data Coordinated Archive and the Space Physics Data Facility at NASA's Goddard Space Flight Center. Additional thanks for maintaining and providing the international sunspot number series goes to the World Data Center – Sunspot Index and Long-term Solar Observations at the Solar Influences Data Analysis Center (SIDC), Royal Observatory of Belgium. The hourly solar wind structure list was kindly provided by Ian Richardson of the NASA Goddard Space Flight Center and CRESST/University of Maryland via the CEDAR Database at the National Center for Atmospheric Research, which is supported by the National Science Foundation.

## Curriculum vitae

Malte Venzmer, born 5 February 1984 in Bremerhaven, Lower Saxony, Germany, finished secondary school (Abitur) at the Gymnasium Ganderkesee in 2003. Subsequently he performed his civilian service working in a care home for disabled persons in Westerland, Sylt.

In 2004 he began to study physics at the University of Konstanz. During his studies, in summer 2008, he did an internship at the Ångström Laboratory, Uppsala University, Sweden, working in the field of materials physics. In 2010/2011 he wrote his diploma thesis in the *Radio- and X-ray astronomy* group of Dr. Jürgen Kerp at the Argelander-Institute for Astronomy, University of Bonn. There, following his diploma in physics, he continued working under a scholarship until end of 2011.

In 2012 he started as a PhD candidate in the *Solar, heliospheric and space weather research* group of Dr. Volker Bothmer at the Institute for Astrophysics, University of Göttingen. During his doctoral studies he worked as a research assistant for several national and international projects. Most of his main results are described in this very thesis.

## notes

Update figures before printing!

Check if footnotes are on same page!

Fragen:

- references vol # fett drucken?
- references journal kursiv drucken?
- maybe style references different. like in space science reviews?
- page # oben lassen?
- A5 format?

nice phrases:

...this leads to the question wh... . The answer to this question is developed in the course of the next section.

write basics without third persons view “we”

define if using astronomical symbols...

...and use style consistently

Letzte Änderungen:

Genehmigungen für die Abb. besorgen!!

check for topic sentences!

Am Anfang der Arbeit den folgenden logischen Aufbau der Kapitel erlaeutern.

Am Anfang jedes Kapitels den folgenden logischen Aufbau der Abschnitte erlaeutern.

Beides auf Aenderungen ueberpruefen.

print figures to check look of colors

adjust figure width to textwidth...

complete pdfinfo text...

Abkuerzungen CME, usw. konsequent nutzen und beim ersten Auftauchen ausschreiben.

englische Kommasetzung beachten!

schauen, ob Kommata oder Punkte durch Semikolon ersetzt werden koennen

Pruefen, ob Ueberschriften den Inhalt des Kapitels gut beschreiben/gut zum Kapitel passen.

check if AE spelling consistently, search and replace: analyse, etc.

check for thin spaces in numbers with 5 digits and more

Header und footer fuer notes, seitenzahl, Thema und Kapitel einfuegen

check gnuplot plot text sizes and finish figures

check for changed links and update access date

sinnlosen Satz irgendwo einfügen

76 %, ACME irgendwo einfügen (ACME is good...)

comic strip aus thesis extrahieren

put movie in header or footer

create hyperref version including bibtex links

adjust link colors and remove boxes... (hyperref package options)

remove google-books links!

maybe adjust References like in Hathaway2010

LaTeX commands:

block commenting: strg+d

strg+shift+d

$$N_{mean_0} = \text{\texttt{e\&e\ e\ e\ e\ e\ e\ e}} \quad (A.1)$$

$$N_{median_0} = \text{\texttt{||| | | | | | | |}} \quad (A.2)$$

Provides generic commands  $\circ$ ,  $^{\circ}\text{C}$ ,  $\%$ ,  $\mu$  and  $\Omega$  which work both in text and maths mode.

[Lem & Kandel \(1984\)](#), ([Lem & Kandel 1984](#)), “`citep[see][page 45]Lem1984`” => (see [Lem & Kandel 1984](#), page 45)

included persons via citations: Volker Bothmer, Rainer Schwenn, Eckhard Bosman, Russel Howard, Manuela Temmer, Angelos Vourlidas, Craig DeForest, Tim Howard, Rodney Viereck

Style rules:

the Sun’s/solar rotation period

Earth’s/terrestrial

the Sun, sunspots; near-Sun measurements, near-relativistic electrons, in situ measurements without hyphen?

64 s data; but 64-second data

Therefore, a comma is set after certain adverbs at the beginning of a sentence.

lognormal or log-normal, not log normal

A&A style:

Italics should never be used for units

italics should be avoided for the following: mathematical signs such as “d” (total differential), “e” (base of natural logarithm), “i” (imaginary unit), “pi”

Physical constants such as the speed of light, the Boltzmann constant, the Hubble constant and the solar mass are also set in regular italics.

$$\text{e}^x = 10 \text{ km s}^{-1} \quad (A.3)$$

$$\text{e}^x = 10 \text{ km}\cdot\text{s}^{-1} \quad (A.4)$$

$$\text{e}^x = 10 \text{ km/s} \quad (A.5)$$

$$k_{\text{B}} \quad (A.6)$$

Sample input: 20 000 km, 1 000 000 s, HD 174 638 1950–1985, p. 11–21, this – written on a computer – is now printed, this—written on a computer—is now printed, signal-to-noise ratio, early-type, metal-poor, non-relativistic  $-30 \text{ K}$ ,  $-5 \text{ }^{\circ}\text{C}$  Dr. h.c. Rockefeller-Smith and Prof. Dr. Mallory

Nützliche Beispiele für LaTeX-Kommandos:

Autobahn

X-Ray

X-Ray

Dr. Huber

100 000 V

100 000 V

The food—which was delicious—reminded me of home.

Red, white, and blue—these are the colors of the flag.

$U = 20\,000 \text{ V}$

solar radius:  $R_{\odot} = 696\,000 \text{ km}$

$10 \text{ }^{\circ}\text{C}$

$10 \text{ }^{\circ}\text{C}$

$10 \text{ }^{\circ}\text{C}$

Ein Winkel von  $10^{\circ}$ .

$$\frac{T_D}{[K]} = 21,8 \cdot \left( \frac{\Delta v_{FWHM}^{LMC}}{[km\ s^{-1}]} \right)^2 \quad (A.7)$$

$$\frac{T_D}{[K]} = 21,8 \cdot \left( \frac{\Delta v_{FWHM}^{LMC}}{[km\ s^{-1}]} \right)^2 \quad (A.8)$$

$$k = 3.56 \text{ e-}6 \quad (A.9)$$

$$k = 3.56 \cdot 10^{-6} \quad (A.10)$$

$$k = 3.56 \times 10^{-6} \quad (A.11)$$

### 1. CM LMC Longitude

drei CM LMC Latitude

Volume in  $(^{\circ})^2 m\ s^{-1}$ . Summe aller Voxel des Objektes.

**Volume** in  $(^{\circ})^2 m\ s^{-1}$ . Summe aller Voxel des Objektes.

- Volume

sdgffs CM GSR Velocity

label

asdf Volume

drei CM LMC Latitude

<sup>1</sup> oder <sup>2</sup>

$$a^2 + b^2 = c^2 \quad (A.12)$$

Formel zitieren: (Siehe Formel A.12, Formel (A.12), Seite 92)

package siunitx:

$20.5 \times 10^{-3} \text{ kg}$

$20.5 \times 10^{-3} \text{ kg}$

$20.5 \times 10^{-3} \text{ kg}$

width defines the width of the resulting box as seen from the outside (This means it can be **smaller** than the material inside the box. You can even set the width to 0pt so that the text inside the box will be typeset without influencing boxes). Besides the length expressions, you can also use

semi-log plots:

log-lin: logarithmic scale on the y-axis, and a linear scale on the x-axis

lin-log: logarithmic scale on the x-axis, and a linear scale on the y-axis

the naming is output-input (y-x), the opposite order from (x, y)

my common language errors:

hyphen for adjectives

solar wind

solar-wind parameters

high-value tail

serial comma (it is an american thing and optional)

a, b, c and d.

a, b, c, and d.

<sup>1</sup>All listed websites were existent on 2008-09-15.

<sup>2</sup>All listed websites were existent on 2008-09-15.

comma if object is at beginning of sentence  
In the case of A, B is C.  
In order to A, B can C.

BE vs AE  
catalogue  
catalog

grey  
gray