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**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.* In view of the planned near-Sun spacecraft mission Parker Solar Probe (PSP) (formerly Solar Probe Plus) the solar wind environment for its prime mission duration (2018–2025) and down to its intended closest perihelion (9.86 solar radii) is extrapolated using in situ data. The PSP mission will be humanity’s first in situ exploration of the solar corona. Visiting this yet uncharted region is of special interest, because 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 solar wind extrapolation of this study is performed within the project Coronagraphic German And US Solar Probe 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 Helios and OMNI in situ 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. The solar wind model is used together with sunspot number predictions to estimate the frequency distributions of major solar wind parameters PSP will encounter during its mission.

*Methods.* The model covers the solar wind’s magnetic field strength and its plasma parameters proton velocity, density and temper- ature. Their individual frequency distributions are represented with lognormal functions. In addition, we also consider the velocity distribution’s bi-componental shape, consisting of a slower and a faster part. The model accounts for solar activity and for solar dis- tance dependency by shifting of these lognormal distributions. We compile functional relations to solar activity by correlating and fitting the frequency distributions with the sunspot number (SSN), using almost five solar cycles of OMNI data. 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. Finally, by combining the found solar cycle and solar distance relations, we obtain a simple dynamical solar wind model for the inner heliosphere, confined to the ecliptic region.

*Results.* The inclusion of SSN predictions and the extrapolation to the PSP perihelion region enables us to estimate the solar wind environment for PSP’s planned trajectory during its mission duration. The estimated solar wind median values during PSP’s first perihelion are 87 nT, 340 km s−1, 4015 cm−3 and 503 000 K. The modeled values for PSP’s closest perihelia are 943 nT, 290 km s−1, 9733 cm−3 and 1 930 000 K, where these velocity and temperature values are clearly overestimated in comparison with existing obser-

vations.

*Conclusions.* This empirical model shows that solar wind acceleration and heating processes below 20 solar radii limit a simple back-extrapolation from existing in situ measurements.

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

# 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 case of Voyager 1 as far away as 138 au1 (July 2017), having even left the heliospause into inter- stellar space at a distance of 121 au (Gurnett et al. 2013). Until today various spacecraft have provided a wealth of solar wind

1 https://voyager.jpl.nasa.gov/

measurements near Earth’s orbit, with WIND (ref.), ACE (Stone et al. 1998) and DSCOVR (Burt & Smith 2012) still 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 (ref.) or MESSENGER (ref.). Ulysses was the first probe that orbited the Sun out of the ecliptic plane and thus could mea- sure solar wind even at polar latitudes (McComas et al. 1998). The Sun-nearest in situ solar wind measurements to date were obtained by the Helios mission. The in 1974 launched Helios 1 spacecraft reached distances of 0.31 au, Helios 2 launched two years later and approached the Sun up to 0.29 au (Rosenbauer et al. 1977). The NASA Parker Solar Probe2 (PSP), formerly Solar Probe Plus, with a planned launch date in mid 2018, will

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

reach after six years in 2024 its closest perihelia at a distance of

9.86 solar radii (*R* ), that is, 0.0459 au (Fox et al. 2015). This distance will 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* ). 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).

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

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The study presented in this paper is undertaken in the Coro- nagraphic German And US Solar Probe 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 3D struc- ture of the solar corona through which the in situ measurements are made to determine the sources of the solar wind. It will pro- vide density power spectra over a wide range of structures (e.g., streamers, pseudostreamers and equatorial coronal holes) for de- termining 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 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 environ- ment is extrapolated down to the closest perihelion of 9.86 *R* 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.

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Generally, two types of solar wind are observed in the he- liosphere, slow and fast streams (Neugebauer & Snyder 1966; Schwenn 1983). Slow solar wind has typical speeds <400 km s−1 and fast solar wind has speeds >600 km s−1 (Schwenn 1990,

p. 144). Their different compositions and characteristics indi- cate 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 discus- sions because several scenarios are possible to explain its origin from closed magnetic structures in the solar corona, such as in- termittent reconnection at the top of helmet streamers and from coronal hole boundaries (Kilpua et al. 2016). The occurrence fre- quency of these slow and fast streams varies strongly with solar activity and their interactions lead to phenomena such as stream interaction regions and for quasi-stationary coronal source re- gions to co-rotating interaction regions (Balogh et al. 1999). Em-

waves ahead (Gosling et al. 1974). Their rate follows the so- lar 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 so- lar 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, there- fore we extrapolate the probability distributions of the major so- lar wind parameters from existing solar wind measurements and take solar cycle dependencies into account. As a baseline we de- scribe the solar wind environment through the key quantities of a magnetized plasma: *density*, *temperature* and *magnetic field strength*. Furthermore, the bulk flow *velocity* is the defining pa- rameter of the two types of solar wind. Solar wind quantities, like flux densities, mass flux and plasma beta, can directly be derived from these four parameters.

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 se- ries with a duration of almost five solar cycles. Their distance de- pendency is derived from Helios solar wind measurements cov- ering more than two third of the distance to the Sun and more than half a solar cycle. From combination of the obtained fre- quency distributions, SSN dependence functions and solar dis- tance dependence functions a general solar wind model is build in Sect. 5, representing the solar activity and distance behavior. Finally, this empirical model is fed with a SSN prediction and extrapolated to PSP’s planned orbital positions in Sect. 6.

# Frequency distributions of the solar wind parameters

The solar wind parameters are highly variable, due to short-term variations from structures like slow and fast wind streams, inter- action regions and CMEs, whose rate and properties depend on the phase of the solar activity cycle. Hence, for deriving char- acteristic frequency distributions for the solar wind parameters, measurements over long-term time spans are needed. The abun- dance of the near-Earth hourly OMNI data set is ideally suited for this purpose, because it spans to date 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. This intercalibrated multi-spacecraft data is time-shifted to the nose of the Earth’s bow shock. The data is ob- tained from the OMNIWeb interface3 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. It should be noted that a test-comparison of hourly av- eraged with higher time resolution data for the available shorter time span 1981–2016 did not show significant differences in our

results.

According to the OMNI data precision and maximal param- eter ranges we specify bin sizes of 0.5 nT for the magnetic field strength, 10 km s−1 for the velocity, 1 cm−3 for the density and

bedded in the slow and fast solar wind streams are transient flows

of coronal mass ejections (CMEs), the faster ones driving shock 3 <http://omniweb.gsfc.nasa.gov/>

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−1, the density in the range 0–117 cm−3, and the tem- perature in the range 3450–6.63 106 K, the mean data values are at 6.28 nT, 436 km s−1, 6.8 cm−3 and 1.05 105 K. These ranges and mean values are as statistically expected from previ- ous analyses of near 1 au solar wind data (e.g., Table 3.3 in Both- mer & 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 ICME with a speed of over 2000 km s−1 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 ob- served in May 1999 with density values even down to 0.2 cm−3 (Lazarus 2000).

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The frequency distributions of the solar wind parameters magnetic field strength, proton density and temperature can well be approximated by lognormal distributions, whereas the pro- ton velocity’s frequency has a differing shape, as shown in Veselovsky et al. (2010). We investigate how well all four so- lar 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

The balancing parameter *c* ensures that the resulting function re- mains normalized as it represents a probability distribution. The fitting of *W*II(*x*) to the velocity’s frequency distribution yields the values of the now five fit parameters (*c*, *x*med,1, *x*avg,1, *x*med,2 and *x*avg,2) as listed in Table 1 together with the median and mean values of the composed distribution, which can be derived via solving

r *W*II(*x*) d*x* = 0 and r *x W*II(*x*) d*x* = 0 . (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 func- tions describe the parameters’ distributions well, but differ for the extreme values, mainly caused by CME events. The simple lognormal fit functions underestimate the frequency of the solar wind parameters in their high value tails, except for the temper- ature’s tail which is overestimated as seen in the insets of Fig. 1. The velocity’s compositional lognormal fit only slightly overes- timates its tail as seen in the inset of Fig. 2. The slow and fast part contribute almost equally (*c* 0.5) to the long-term velocity distribution function.

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*W*(*x*) = 1 exp

√

σ 2π*x*

(ln *x* µ)2

− 2σ2

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(1)

discuss high value zoom figures; read in Veselovsky2010

# Solar activity dependence of the solar wind

depends on the location µ and the shape parameter σ. Changes in µ affect both the horizontal and vertical scaling of the function whereas σ influences its shape. The distribution’s median *x*med and mean *x*avg (average) positions are straightforward to inter- prete and are directly calculated from µ and σ:

*x*med = exp (µ) ⇐⇒ µ = ln (*x*med) , (2)

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# 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 sunspot number, being a commonly used long-term so- lar activity index, and determine the time lags with the highest

*x*avg = exp

µ + σ

2

2

⇐⇒ σ =

2 ln

*x*avg

*x*med

. (3)

correlation coefficients.

The international sunspot number (1963–2016) is provided by the online catalogue4 at the World Data Center – Sunspot

It is apparent that the mean is always larger than the median. Re- placing the variables µ and σ with these relations, the lognormal function (1) becomes

Index and Long-term Solar Observations (WDC-SILSO), Solar Influences Data Analysis Center (SIDC), Royal Observatory of Belgium (ROB).

For the correlations we fit lognormal functions to the fre-

1 

 4 ln *x*med

*x*

ln2 *x*

med

r *x*

, 

quency distributions as in Sect. 2, but implement linear relations to the yearly SSN, allowing shifting of the distribution functions

*W*(*x*) =

r ,

2 /π ln

*x*avg

*x*med

exp − r *x*avg ,  . (4)

with SSN. For the velocity the approach is different insofar as its two components are kept fixed and instead their balance is

The values of *x*med and *x*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, density and temperature dis- tributions well, as can be seen in Fig. 1. However, for the velocity the fit function appears not to be as good in describing the mea- sured 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 Ta- ble 1, 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). There- fore a compositional approach is chosen by combining two log- normal functions (4), involving more fit variables:

*W*II(*x*) = *c* · *W*1(*x*) + (1 − *c*) · *W*2(*x*) . (5)

modified with the changing SSN.

Fig. 3 shows yearly medians of the solar wind parameters and the yearly SSN together with the solar cycle number. The reason for correlating the SSN to the 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 vari- ations 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 is correlated with the presence of polar coronal hole extensions to lower latitudes being a typical feature of the solar cycle, being the reason for the common velocity peak in the de- creasing phase of the SSN, as pointed out by Bothmer & Daglis (2007, p. 75, Figure 3.52). Therefore the solar wind velocity, density and temperature maxima exhibit time-lags to the SSN maxima.

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

**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 also the fit parameters of the double lognormal function (5) are listed, as well as the median and mean values of the resulting velocity fit. The mean absolute errors and sums of absolute residuals are also listed. The values in brackets are the estimated standard deviations of the fit parameters.

Parameter Median*a* Mean*a* Balance MAE SAR

*x*med *x*avg *c* [10 ] [%]

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|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Magnetic field  Velocity | 5.661(16)  4.085(19) | 6.164(18)  4.183(20) | – 5.51  – 18.0 | 6.83  18.69 |
| Density | 5.276(24) | 6.484(34) | – 5.49 | 6.48 |
| Temperature | 7.470(17) | 11.301(32) | – 0.871 | 5.78 |
| Velocity *W*1 4.89(14) | | 5.00(14) 0.504(62) – | | –  – |
| *W*II 4.16(14)*b* | | 4.42(14)*b* | – 3.98 | 4.20 |

*W*2 3.68(20) 3.72(20) –

**Notes.** (*a*) In units of nT, 102 km s−1, cm−3 and 104 K. (*b*) Error estimates derived from the individual fit part errors.

figures/histogram\_fits\_4\_a\_zoom\_paper\_pdfplot.pdf

**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−1, 1 cm−3 and 10 000 K. The fits’ median and mean values are indicated as well. The insets show zoomed-in frequency axes.

The correlation coefficients of the solar wind parameters with the yearly SSN shown in the bottom part of Fig. 3 are cal- culated for time lags back to 15 years to cover a time span longer than a solar cycle. As expected, the correlation coeffi- cients’ amplitudes of all parameters decline with increasing time lag and show a frequency of about 11 years. The highest corre- lation coefficient of 0.728 to the SSN is found for the magnetic field strength, it has no time lag. This finding is anticipated be- cause the SSN is found to be directly proportional to the evolu- tion of the photospheric magnetic flux (Smith & Balogh 2003). Velocity and temperature show a lag time of 3 years with peak

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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 by Bougeret et al. (1984) reported den- sity anticorrelation to the SSN.

To enable shifts of the solar wind frequency distributions with the SSN, we add a linear SSN dependency to the median

*x*med(*ssn*) = *a*med · *ssn* + *b*med , (7)

using a factor to the SSN *a*med with a baseline *b*med. We relate the mean with a scaling factor to the median to transfer its SSN

then fitted to the yearly data. The three resulting fit coefficients (*a*med, *b*med and *a*avg) are presented in Table 2.

As can be seen from Fig. 4, naturally, the fit models match with the general data trends, 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

figures/histogram\_fits\_V\_a\_zoom\_dbl\_paper\_pdfplot.qpuditfe similar slope as shown in Fig. 5.

Again, the solar wind velocity needs a special treatment be- cause of the application of the double lognormal distribution (5). Since it is well known that slow and fast solar wind stream oc- currence rates follow the solar cycle and basically maintain char- acteristic speeds (ref.), we keep the two velocity components’ positions constant and vary instead their balance with the SSN:

*c*(*ssn*) = *ca* · *ssn* + *cb* . (9)

**Fig. 2.** The velocity’s 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 has a zoomed-in frequency axis.

figures/OMNI\_yearly\_ssn\_correlation\_c\_plot.pdf

**Fig. 3.** The solar wind parameter yearly medians 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).

dependency:

*x*avg(*ssn*) = (1 + *a*avg) · *x*med(*ssn*) . (8)

The fit result (see Table 2) yields a model in which three years after solar cycle minimum (SSN of zero) the contribution of slow solar wind to the overall solar wind distribution reaches a maxi- mum value of about 64 % and decreases with increasing SSN as shown in Fig. 6.

To investigate the amount of slow and fast wind contribu- tions depending on solar activity, we apply the commonly used constant velocity threshold of vth = 400 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). Specific ve- locity thresholds between slow and fast solar wind cannot be directly compared with the to some degree steeper balance pa- rameter of the double fit function used in this model. However, it appears being likely a more realistic approach than just taking a specific velocity threshold for the slow and fast wind, in agree- ment with the overlapping nature of the velocity flows reported by McGregor et al. (2011a).

# Solar distance dependency

In order to derive heliocentric distance relationships of the bulk solar wind distribution functions, we apply and fit a power law dependency to the Helios data. We evaluate the fits’ extrapola- tion behavior in direction to the Sun, because in a subsequent step it will be extrapolated 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 cy- cle minimum, the data of both probes cover the rise to the maxi- mum of cycle 21, covering 6.5 years at varying distances to the Sun.

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In the same way as the OMNI data we investigate hourly av- erages of the Helios data. The Helios 1 merged hourly data from the magnetometer and plasma instruments (Rosenbauer et al. 1977) include 12.5 orbits for the time range 10 December 1974

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until 14 June 1981, those for Helios 2 include 8 orbits for the

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time span 1 January 1976 until 4 March 1980. The data are re- trieved from the Coordinated Data Analysis Web (CDAWeb) in- terface at NASA’s GSFC/SPDF5.

The Helios 1 magnetometer data coverage for this data set is about 43 % (i.e., 2.8 years), 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

With the implementation of these relations into the lognor-

mal function (4), the new dynamic fit function *W*'(*x*, *ssn*) is 5 <http://spdf.gsfc.nasa.gov/>

**Table 2.** Resulting fit coefficients from the OMNI data fitting with lagged SSN. For the velocity the fit parameters from the double lognormal fit and their balancing function are given. The values in brackets are the estimated standard deviation of the fit parameters.

Median*a* Mean Balance SSN factor *a*med Baseline *b*med Scaling factor *a*avg SSN factor *ca* Baseline *cb*

Magnetic field 1.309(19) × 10−2 4.285(17) 8.786(78) × 10−2 – –

Parameter

Density 3.81(25) × 10−3 4.495(26) 3.050(27) × 10−1 – –

Temperature 1.974(26) × 10−2 5.729(19) 6.541(28) × 10−1 – –

−1.799(95) × 10− 0.638(32)

Velocity *W*1'

*W*2'

– 3.633(12) 1.008(37) × 10−2 3

– 4.831(81) 2.31(20) × 10−2

**Notes.** (*a*) In units of nT, 102 km s−1, cm−3 and 104 K.

figures/OMNI\_yearly\_BVdblNTSSN\_fit\_e\_plot.pdf

**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 for the models shifted SSN are indicated by grey and black lines. The velocity median is derived from the SSN weighted constant lognormal parts (dotted lines).

of Helios 2. Thus, using this data, one has to keep in mind that its time coverage is unequally distributed over the solar cycle. Considering the data gap distributions, the amount of data dur- ing solar cycle minimum up to mid 1977, that is, the transition from minimum to maximum, covers about 68 % whereas during maximum of cycle 21 data are available only 38 % of the time. This Helios data bias towards solar minimum is the 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 median and mean values of the key solar wind parame- ters for different solar distances of the Helios data are calculated for the minimal distance resolution 0.01 au of the data set, see Fig. 7. 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* · *re* (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 fit coefficients (*d*med, *d*avg, *e*med and *e*avg) are listed in Table 3.

As anticipated, 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 sep- arately for the fast and the slow solar wind as *B*fast ∝ *r*−1.54 and *B*slow ∝ *r*−1.61. The velocity exponent matches with the values

**Table 3.** Fit coefficients for the median and mean solar distance dependencies of the four solar wind parameters derived from the combined Helios 1 and 2 data. The errors in brackets are the estimated standard deviations of each fit parameter. 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.

Median Mean Crossing distance Yearly variation

*d*med*a e*med *d*avg*a e*avg [au] ∆*e*

Parameter

Magnetic field 5.377(92) −1.655(17) 6.05(10) −1.546(18) 0.339(11)

Velocity 4.107(28) 0.058(13) 4.356(24) 0.049(10) 0.7(83) × 103

0.11

0.012

Density 5.61(27) −2.093(46) 7.57(30) −2.010(38) 0.027(73) 0.072

Temperature 7.14(23) −0.913(39) 9.67(21) −0.792(28) 0.082(85) 0.005

**Notes.** (*a*) In units of nT, 102 km s−1, cm−3 and 104 K.

**Fig. 5.** Solar wind parameter median 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 stan- dard deviation and the relative weight from the yearly data coverage. The SSN dependent median (7) is derived from the lognormal model fit (dashed line). For the velocity the median is derived from the SSN weighting (9) of the slow and fast model parts, whose magnitudes are SSN independent (dotted line).

figures/OMNI\_yearly\_BVNTvsSSN\_a.pdf

figures/Vdbl\_SSN\_ratio\_f\_plot.pdf

**Fig. 6.** Ratio of slow to fast solar wind for a by 3 years lagged SSN. The yearly ratios (+) and their weighted linear fit (solid line) are obtained from OMNI data with a threshold velocity of vth = 400 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.

found by Schwenn (1983, 1990), who derived the distance de- pendencies for both Helios spacecraft separately as vH1 *r*0.083 and vH2 *r*0.036. The calculated density exponent agrees well with the Helios plasma density model derived by Bougeret et al.

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(1984), yielding *n r*−2.10. The temperature exponent 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*fast ∝ *r*−0.74 and *T*slow ∝ *r*−0.58.

Fig. 7 shows the radial dependence of the solar wind param- eters over the distance range 0.29–0.98 au and the mean and me- dian values and their respective power law fits. The mean and median velocity fit exponents are very similar, which indicates that they just as well can be kept identical so that the basic shape of the frequency distribution does not change with distance. Con- trary, the mean and median fits for the magnetic field strength cross each other at 0.339 au and the mean is lower than the me- dian at smaller distances (Table 3). Thus, below that distance the distribution function cannot well be described anymore by a log- normal function. The fits for the proton temperature show a sim- ilar behavior, having an 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. To circumvent such limitations we set the exponents *e*med and *e*avg to be identical for all four parameters. It should be noted that this simplification leads to slightly larger modeling errors, especially in case of the magnetic field strength.

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Next we retrieve the frequency distributions of the four pa- rameters in distance bins of 0.01 au, choosing the same resolu- tion as for the OMNI data analyzed in Sect. 2—the distributions are plotted in Fig. 8. For simplification, as mentioned before, we treat the exponents of the median and mean fit functions as being identical. Implementing the power law distance dependency (10)

into the lognormal function (4), we get the fit parameters (*d*m' ed,

*d*a'vg and their common exponent *e*'). Again, we use the double lognormal function (5) for the velocity distribution fit, resulting in *W*I'I'(*x*, *r*). The additional fit parameters are the balancing pa-

rameter *c*' and for the second lognormal part *d*m' ed,2 and *d*a'vg,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), be- cause with a mean SSN of 59 during the Helios time period, *c*(59) = 0.53, as can be seen from Fig. 6.

The frequency distribution data for the four solar wind pa- rameters with respect to the radial distance from the Sun are plot- ted in Fig. 8, together with their power law lognormal fits and the double lognormal fit for the velocity 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 distance independent shape approximation applied. The velocity and temperature models’ upper values show a higher abundance than the actual data, see also zoom boxes in Figs. 1 and 2.

figures/radial\_fit\_4\_thesis\_light\_skip\_pdfcairo\_plot.pdf

**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 abundance visible in these plots, we added a random distance value of up to ±0.005 au.

**Table 4.** Fit coefficients from the single lognormal power function, respectively double lognormal for the velocity from the combined Helios data. The errors in brackets are the estimated standard deviations of the fit parameters.

Parameter Median*a* Mean*a* Exponent Balance

*d*m' ed *d*a'vg *e*' *c*'

Magnetic field 5.358(25) 5.705(28) −1.662(11) –

Density 5.424(33) 6.845(47) −2.114(20) –

Temperature

''

6.357(64) 10.72(14) −1.100(20) –

Velocity *W*1 3.707(13) 3.748(16) 0.0990(51) 0.557(45)

*W*2''

*W*I'I'

5.26(13) 5.42(11)

4.13(13)*b* 4.47(11)*b* – –

**Notes.** (*a*) In units of nT, 102 km s−1, cm−3 and 104 K. (*b*) Velocity median and mean 1 au values for the resulting function. Error estimates derived from the individual fit part errors.

# 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 distribu- tions’ solar activity relationships and their distance dependencies derived from the OMNI and Helios data. The result is an empir- ical solar wind model for the inner heliosphere which will then be extrapolated to the PSP orbit in Sec. 6.

This established solar wind model for the radial distance de- pendence is representative for the time of the Helios observa- tions around the rise of solar cycle 21. The variation of yearly power law fit exponents 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. However, for simplicity we assume, that the distance scaling laws can be treated as time independent and include the calculated exponents’ yearly variations ∆*e*, sum- marized in Table 3, as relative uncertainties.

Since we neglect possible variations of the distance scaling laws, we combine the frequency distribution’s median solar ac- tivity dependency (7) derived for 1 au from the OMNI data with the power law exponents (10) derived from the Helios data:

*x*med(*ssn*, *r*) = (*a*med · *ssn* + *b*med) · *re*' . (11)

figures/mixed\_fit\_fixed\_4\_paper\_f\_plot.pdf

**Fig. 8.** Frequency distributions of the four solar wind parameters with respect to the 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.

**Fig. 9.** Helios yearly variation of the solar wind parameters’ fit expo- nents together with the SIDC 13-month smoothed monthly SSN. The weighted standard deviations are indicated with dotted lines. In this plot the year 1974 is omitted because of merely 21 days since Helios launch that year.

figures/yearly\_gradients\_b.pdf

Thus we obtain the combined model function *W*'''(*x*, *ssn*, *r*) and for the velocity *W*I'I''(*x*, *ssn*, *r*) with the double lognormal func- tion (5).

# Model extrapolation to PSP orbit

To estimate PSP’s solar wind environment during its mission time for its orbital positions, SSN predictions are included into the in the previous sections derived empirical solar wind model and extrapolations down to the PSP perihelion region are per- formed.

Parker Solar Probe is planned to launch in mid 2018. With its first Venus flyby it will swing into Venus’ orbital plane, reaching already 93 days after launch in November 2018 a first perihelion with a distance of 0.16 au. Seven additional Venus flybys allow to finally reduce its perihelion distance to a minimum of 9.86 *R* (Fox et al. 2015) as plotted in Fig. 11.

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We extrapolate the derived empirical solar wind model (11) to PSP’s orbital distance range and compare the results with those from the existing models shown in Fig. 10.

The magnetic field strength is found to increase from me- dian values of about 43 nT at 0.25 au to 715 nT at 0.046 au for a SSN of 0. Taking a SSN of 200 increases the value to 69 nT at 0.25 au and 1152 nT at 0.046 au. Our extrapolation results are slightly flatter than those derived from the analytical magnetic field model by Banaszkiewicz et al. (1998), who constructed a dipole plus quadrupole plus current sheet (DQCS) model. This difference is arguably due to the previously mentioned (Sect. 4) with solar distance changing shape of the frequency distribution, which for smaller distances deviates more from the model’s log- normal distribution.

figures/sw\_extrapolation\_ssn\_b\_plot.pdf

**Fig. 10.** Radial extrapolation of the solar wind parameters to the PSP orbit region. The from Helios and OMNI measurements obtained models are extrapolated to the PSP region—for the extreme cases of solar minimum (SSN = 0) and maximum (SSN = 200). Note that there is a time lag to the SSN depending on the solar wind parameter. The magnetic field radial dependence is slightly flatter than the analytic DQCS model for solar minimum which Banaszkiewicz et al. (1998) derived. Below 20 *R*0 the slow wind velocity is overestimated in comparison to the measurements from Wang et al. (2000)) and Sheeley et al. (1997). Down to PSP’s perihelion the density is in good agreement with the model from Leblanc et al. (1998). to 1-column...?

The average velocity is found to decrease from 340 km s−1 at

0.25 au to about 290 km s−1 at 0.046 au for a SSN of 0. Whereas using a SSN of 200 it decreases from 390 km s−1 to 330 km s−1. Comparing the results with those found by Sheeley et al. (1997) and Wang et al. (2000) shows an overestimation in our extrap- olated velocity values for distances below 20 *R* . They used LASCO coronagraph observations to track moving coronal fea- tures (blobs) in the distance range 2–30 *R* 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 (Parker 1958). Therefore, it gener- ally can be expected that PSP will encounter a slower solar wind environment close to the Sun than our model estimates and thus PSP will measure solar wind acceleration processes below 30 *R* (Sheeley et al. 1997; McComas et al. 2008).

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The proton density increases from about 84 cm−3 at 0.25 au to about 3018 cm−3 at 0.046 au for a SSN of 0. Being almost in- dependent 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

The extrapolated proton temperature increases from about 260 000 K at 0.25 au to about 1 690 000 K at 0.046 au for a SSN

of 0 and from 440 000 K to 2 860 000 K for a SSN of 200. Know- ing that near-Sun coronal temperatures are in the range of 2– 3 MK (Billings 1959; Liebenberg et al. 1975), the model may overestimate the extrapolated temperatures at the PSP perihelion distance. The results can be compared to...

For SSN short-term predictions several sources are available. The SIDC provides 12-month SSN forecasts6 obtained from dif- ferent methods (e.g., Kalman filter combined method). The SSN prediction of NOAA’s Space Weather Prediction Center (SWPC) follows for the time period until end of 2019 a consensus of the Solar Cycle 24 Prediction Panel7. For the prediction of the next solar cycle we simply assume a pattern similar to the last cycle and thus shift the last cycle by 11 years. Additionally we con- sider as possible alternatives SSN patterns of half and twice its amplitude as shown in Fig. 11. The SSN for PSP’s first perihe- lion will be small—certainly below 20, whereas PSP’s closest perihelia, which commence at the maximum phase of cycle 25 end of 2024, will experience as of now incalculable SSN ampli- tudes.

radio burst observations. Their model shows that the density dis-

tance dependency scales with *r*−2 and steepens just below 10 *R* with *r*−6. For the comparison we assumed a solar wind helium abundance of 5 %.

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

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

figures/SPP\_orbit\_predicted\_SSN\_overview\_e\_plot.pdffigures/SPP\_perihelia\_prediction\_nearest\_e\_plot.pdf

**Fig. 11.** 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 prediction, SWPC prediction and by 11 years shifted SSN from previous cycle 24, together with two alternative trends of half and twice its amplitude.

figures/SPP\_perihelia\_prediction\_e\_plot.pdf

**Fig. 12.** Estimated solar wind parameter medians (black lines) and their error bands (grey) 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).

Implementing the predicted SSN for the PSP mission time and the orbital trajectory data, we can finally derive the estimated solar wind environment *W*'''(*x*, *ssn*, *r*), to infer which solar wind parameter magnitudes can be expected.

Figs. 12 and 13 show the considered different solar wind parameters for 12-day periods, comprising the first perihelion in Novemver 2018 and the closest perihelion in December 2024. In the beginning of the mission peak median values of about 87 nT, 340 km s−1, 4015 cm−3 and 503 000 K are esti- mated to be measured at 0.16 au, increasing to about 943 nT, 290 km s−1, 9733 cm−3 and 1 930 000 K during the closest ap- proach at 0.046 au.

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**Fig. 13.** Estimated solar wind parameter medians (black lines) and their error bands (grey) during during 12 days in 2024 with PSP’s nearest perihelion at 0.0459 au. For the velocity the combined median is cal- culated and also the SSN independent slow and fast parts are plotted (dotted lines).

# Discussion

We started the development of the empirical solar wind environment modelling for the near ecliptic PSP orbit described in detail in the previous sections, including the mathematical methods and statistical errors, by lognormally fitting the about 50 years of solar wind data obtained by near Earth satellites inter-calibrated data collected in the OMNI database, using the frequency distributions of the key solar wind parameters velocity V, density N, temperature T and magnetic field strength B. The database covers almost five solar cycles and thus represents solar wind gathered at different phases of solar activity in the ecliptic plane, with a negligible asymmetry in terms of activity. In the next step we have investigated the yearly variation of the solar wind distribution functions along with the SSN over 50 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. The derived power law fit functions were used to scale the formerly calculated 1 AU distribution fit functions to the PSP orbit, correlated with SSN predictions for the year 2018-2025, i.e. for the prime mission phase that gets PSP to a closest perihelion of 9.86 solar radii distance to the Sun. The reason for performing the analysis this way is based on the fact that the OMNI 1 AU solar wind database is much larger than the Helios data base. However, it is clear that the calculated distribution functions just 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, as shown by xxx (ref.), or the evolution and interaction of individual solar wind streams and superimposed CMEs and shocks. However, the derived results are in good comparison with existing models for the solar wind density and magnetic field strength as shown in section 6. The velocity and temperature extrapolations indicate that PSP will dive indeed into the acceleration and heating regions of the solar wind to be expected below 20 solar radii (see Figure 11).

The near-Sun solar wind velocity at PSP perihelion is also expected to be slower than our model estimates, because the region of the Alfvénic critical source surface up to which the solar wind is believed to be accelerated is predicted to lie between 15–30 *R* (Schatten 1969, Sittler1999, Exarhos2000, Katsikas2010, Goelzer2014),

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In our study we have not investigated the occurrences of extreme solar wind parameters caused by CMEs or enhanced values due to stream interaction (SIs) or co-rotation interaction regions. The Helios solar wind measurements plotted over radial distance in Figure 7 show several extreme values far above the usual solar wind speeds, densities, magnetic field strengths and temperatures likely to be associated with individual CMEs. The results by Srivastava et al. (2017) indicate that due to the solar wind drag the speeds of fast CMEs will commonly slow down substantially up to distances of 40 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.

To be moved!

The OMNI data are time-shifted to the nose of the Earth’s bow shock. This leads to yearly solar distance variations of >2 % as the Earth orbits the Sun. The error estimation over the year caused by this varying radial difference can be expected to be smaller than 5 % derived from investigation of the power law exponents of the solar wind parameters. Furthermore, the Earth’s orbit varies over the course of the year by 7.2◦ in heliographic latitude. Schwenn (1990), Bruno (ref.) and Balogh et al. (1999) have pointed out that the solar wind parameters also vary with latitudinal separation from the heliospheric current sheet (HCS), but this aspect is beyond the scope of this study.

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# Summary of the results

For the near Earth solar wind OMNI data, and the Helios 1 and 2 data obtained over the distance range 0.3-0.98 AU we derived lognormal fits of the frequency distributions’ shapes of the four key solar wind parameters magnetic field strength B, proton velocity V, proton density N and proton temperature T. These dependencies of the distribution functions on the solar activity cycle and on radial distance to the Sun have been modelled and extrapolated to the Parker Solar Probe orbit, with a minimum perihelion of 9.86 RS in 2015, taking into account predictions of the sunspot number. This empirical CGAUSS solar wind model for PSP yields the following main results for the normal solar wind without extreme values possible in extreme CME events …:

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The velocity and temperature values are overestimated below 20 *R* in comparison with existing observations. This shows that solar wind acceleration and heating processes below 20 *R* limit the simple back-extrapolation from existing in situ measurements.

WISPR mission operations implications...

Implications for SoloHI on Solar Orbiter …

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