# The solar wind's geomagnetic impact and its Sun–Earth evolution

Predictive models for space weather and for the Parker Solar Probe orbit

PhD defense by *Malte Venzmer*


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Thursday, 1 November 2018, 14:00



## The two studies in my thesis


The solar wind's geomagnetic impact and its Sun–Earth evolution

Predictive models for space weather and for the Parker Solar Probe orbit


**Geomagnetic impact of the solar wind**

I derived relations to predict geomagnetic activity from

- Solar wind electric field
- Velocity of coronal mass ejections
- Velocity of solar wind streams

**Empirical solar wind model**

I use existing solar wind data to derive

- Solar wind model for the inner heliosphere
- Extrapolation to the near-Sun region
- Prediction for Parker Solar Probe orbit

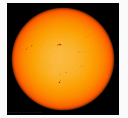








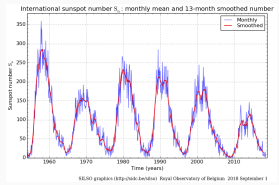
## Solar activity



Credit: NASA SDO/HMI, 16 May 2013

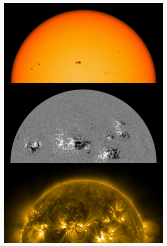
Credit: NASA SDO/HMI, 28 October 2014

11-year sunspot number cycle

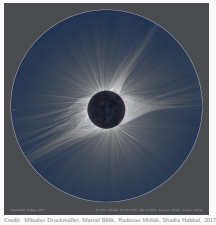





## Solar activity



Credit: NASA SDO/HMI and SDO/AIA, 16 May 2013



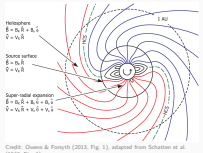
Credit: Miloslav Druckmüller, Marcel Bělík, Radovan Měřták, Shadia Habbal, 2017



## Solar wind

Solar wind

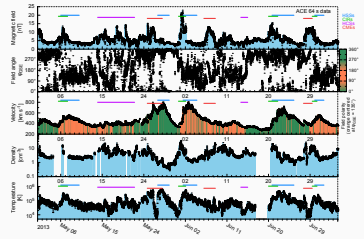
- Theoretical model (Parker, 1958)
  - Expanding isothermal solar atmosphere
  - Parker spiral field geometry
- In-situ measurements confirmed its existence in 1959
- Monitored continuously near Earth since




Credit: Owens & Forsyth (2013, Fig. 1), adapted from Schatten et al. (1969, Fig. 1)



## Solar wind

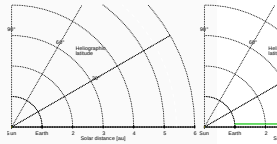





## Solar wind

Measured in-situ throughout the heliosphere:

- Voyager 1 & 2 – out to heliopause (1–120 au)
- Helios 1 & 2 – down to Mercury (0.29–0.98 au)
- Ulysses – up to high heliolatitudes (±79°)






## Solar wind

Credit: Miloslav Druckmüller, Zuzana Druckmüllerová, Jana Hoderová, Peter Šťastka, Shadia Habbal, 2017

The near-Sun region is of special scientific interest:

- Coronal heating problem
- Solar wind acceleration



## Parker Solar Probe

Parker Solar Probe mission to fly within 10 $R_\odot$ of the Sun

Primary goals (Fox et al., 2015):

- Trace flow of energy that heats and accelerates the corona and solar wind
- Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind
- Explore the mechanisms that accelerate and transport solar energetic particles

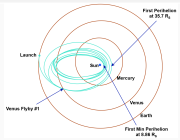
**Scientific instruments**

- FIELDS – Electromagnetic Fields Investigation
- IS☉IS – Integrated Science Investigation of the Sun
- SWEAP – Solar Wind Electrons Alphas and Protons Investigation
- WISPR – Wide-Field Imager for Solar Probe



## Parker Solar Probe

Credit: NASA/Johns Hopkins APL/Ed Whitman, 2018




Credit: NASA/Johns Hopkins APL, 2018

| | |
|---|---|
| Launch | 12 August 2018 |
| 1st Venus flyby | 3 October |
| Sun-closest spacecraft ever | 29 October |
| 1st perihelion at 36.7 $R_\odot$ | 6 November |
| ... | ... |
| 22nd perihelion at 9.86 $R_\odot$ | 24 December 2024 |









## Empirical solar wind model

Aim of this study:

- use existing solar wind data
- build empirical solar wind model
- extrapolate model to PSP orbit

The major part of this study is published in Venzmer & Bothmer (2018)

The article is based on my work performed for the CGAUSS (Coronagraphic German and US SolarProbePlus Survey) project

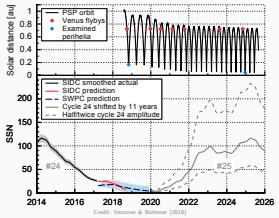
Concept of the model:
Frequency distributions shifted according to solar activity and solar distance

**Solar wind key parameters**

- Magnetic field strength
- Velocity
- Density
- Temperature



## PSP distance and solar activity




Credit: Venzmer & Bothmer (2018)

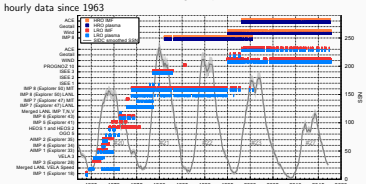
Perihelion #1
2018: solar minimum

Perihelion #22
2024: solar maximum



## Solar wind data

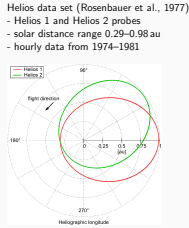
OMNI data set (King & Papitashvili, 2005)
- intercalibrated multi-spacecraft data
- time-shifted to the bow shock of the magnetosphere
- hourly data since 1963

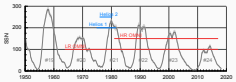





## Solar wind data

Helios data set (Rosenbauer et al., 1977)
- Helios 1 and Helios 2 probes
- solar distance range 0.29–0.98 au
- hourly data from 1974–1981



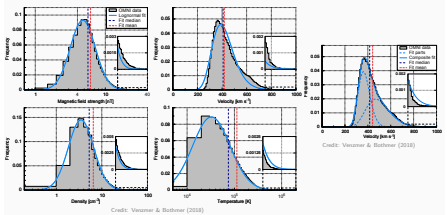




**Solar wind model data use**

- 53 years of hourly near-Earth OMNI data to derive
  - frequency distributions
  - solar activity dependencies
- Hourly data from both Helios probes between 0.29–0.98 au to derive
  - solar distance dependencies

## Frequency distributions

Hourly OMNI data from 1963 to 2016

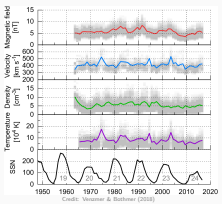


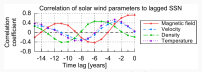
Credit: Venzmer & Bothmer (2018)



## Solar activity dependence

Hourly OMNI data from 1963 to 2016

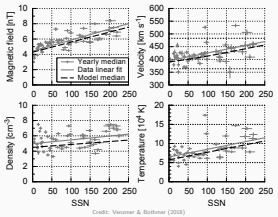




Credit: Venzmer & Bothmer (2018)



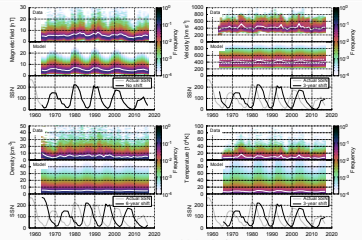
## Solar activity dependence



Credit: Venzmer & Bothmer (2018)



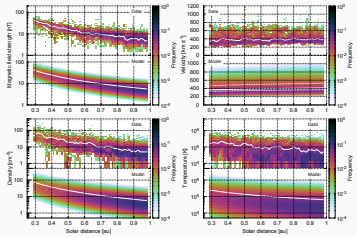
## Solar activity dependence



Credit: Venzmer & Bothmer (2018)



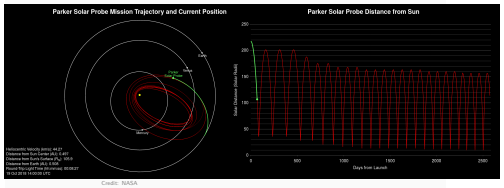
## Solar distance dependence – Helios data



Credit: Venzmer & Bothmer (2018)



## Prediction for PSP orbit

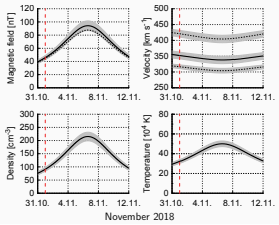



Credit: NASA



## Prediction for PSP orbit

Perihelion #1

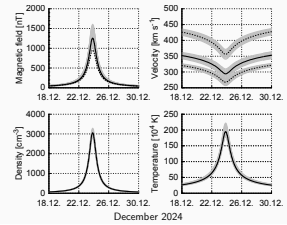


November 2018



## Prediction for PSP orbit

Perihelion #22 (first closest)



December 2024



## Comparison with other studies

**Predicted values at 9.86 $R_\odot$**

$B = 1241\,\mathrm{nT}$
$v = 290\,\mathrm{km\,s^{-1}}$
$n = 2951\,\mathrm{cm^{-3}}$
$T = 1.93 \times 10^6\,\mathrm{K}$

- Magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)
- Remote studies reveal slow wind velocities of $200\,\mathrm{km\,s^{-1}}$ (Sheeley et al., 1997; Wang et al., 2000)
- Density values agree well with radio burst observations (Leblanc et al., 1998)
- Near-Sun coronal temperatures yield 2–3 MK (Billings, 1959; Liebenberg et al., 1975)

**Extrapolation results (Venzmer & Bothmer, 2018)**

- Remote observations show the limits of the extrapolation
- Velocity and temperature are overestimated
- Solar wind is still being heated and accelerated in this region (up to 20 $R_\odot$)





## Summary

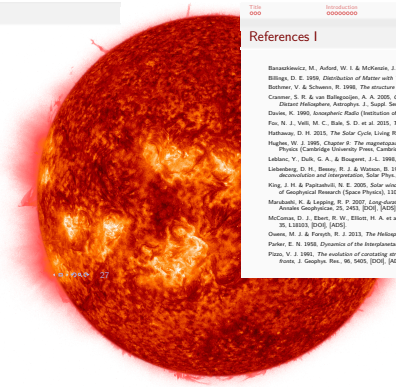
- I derived an empirical solar wind model for the inner heliosphere. It considers
  - frequency distributions of the key solar wind parameters
    - magnetic field strength
    - velocity
    - density
    - temperature
  - solar activity via the sunspot number
  - solar distance
- The model is extrapolated to the near-Sun region
- The solar wind environment is predicted for the orbit of PSP



## Outlook

- Possible modifications to model (e.g., flux conservation)
- Refine model with additional solar wind data from Mercury probes and the upcoming Solar Orbiter mission
- Parker Solar Probe measurements can be used to validate the extrapolations

Thank you!







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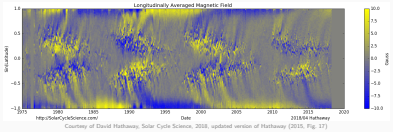
Wang, Y.-M., Sheeley, N. R., Socker, D. G., Howard, R. A. & Rich, N. B. 2000, *The dynamical nature of coronal streamers*, J. Geophys. Res., 105, 25133, [DOI], [ADS].






## Solar activity

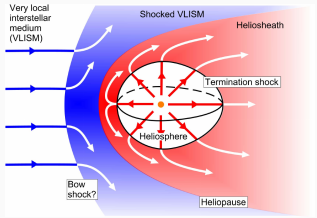
Magnetic butterfly diagram



Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)



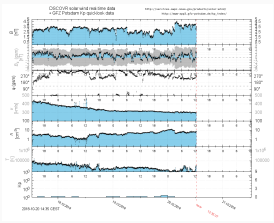
## Solar wind



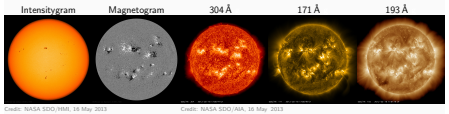

Credit: Owens & Forsyth (2013, Fig. 9)



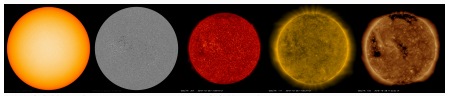
## Solar wind



## Solar surface and atmosphere



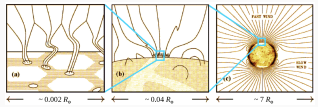

Credit: NASA SDO/HMI, 16 May 2013 Credit: NASA SDO/AIA, 16 May 2013



Credit: NASA SDO/HMI, 28 Oct ober 2018 Credit: NASA SDO/AIA, 28 October 2018



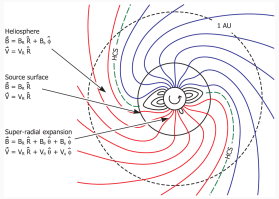
## Solar magnetic field




Courtesy of S. R. Cranmer



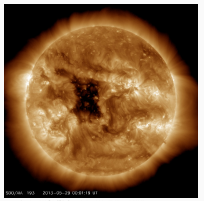
## Solar magnetic field




Credit: Owens & Forsyth (2013, Fig. 1), adapted from Schatten et al. (1969, Fig. 1)



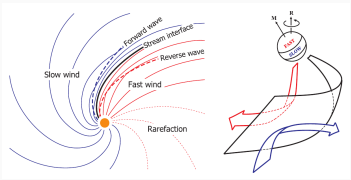
## Slow and fast solar wind



Credit: NASA, SDO and the AIA, EVE, and HMI science teams



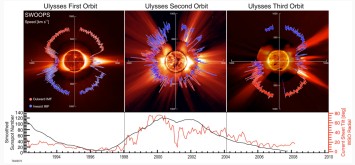
## Slow and fast solar wind




Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)



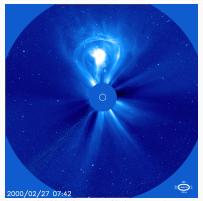
## Solar activity



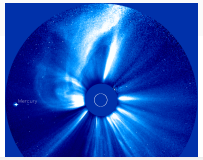

Credit: McComas et al. (2008a, Fig. 1)

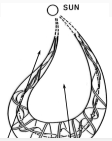


## Coronal mass ejections



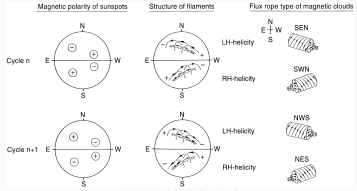

Courtesy of SOHO LASCO consortium. SOHO is a project of international cooperation between ESA and NASA







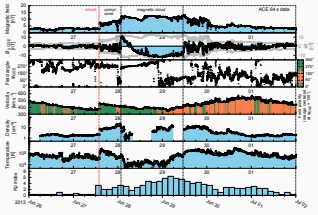

## CME orientation




Credit: Bothmer & Schwenn (1998, Fig. 10)

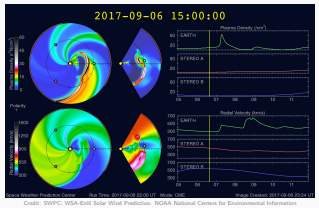


## In-situ CMEs





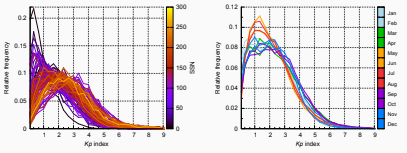

## Solar wind and CME forecast




Credit: SWPC. WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information



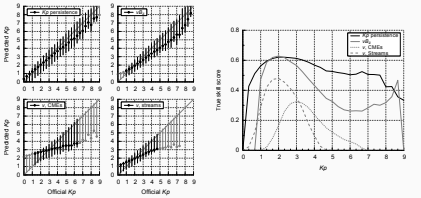
## *Kp* long-term variations





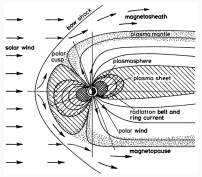



## Prediction performance






## Magnetosphere



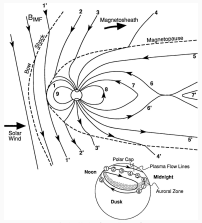

Credit: Davies (1990, Fig. 2.12)

Interaction mechanisms between solar wind and magnetosphere:

- Reconnection
- Turbulence
- Compression
- Induction



## Magnetosphere




Credit: Hughes (1995, Fig. 6.11)

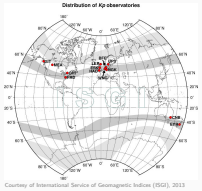
Factors that influence the reconnection flux rate:

- Velocity
- Magnetic field strength
- Magnetic field angle
- Size of reconnection region



## *Kp* index

- Planetary geomagnetic disturbance indicator
- 3-hourly variation maxima
- 13 observatories at 50° geomagnetic latitudes
- Scale from 0 to 9

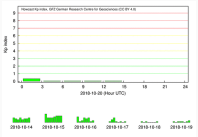



Courtesy of International Service of Geomagnetic Indices (ISGI), 2013



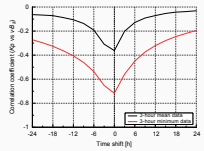
## *Kp* index

Quicklook *Kp*



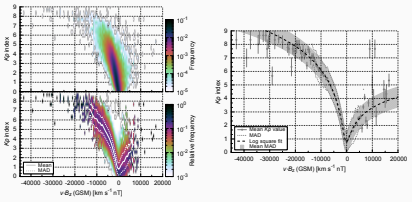

Credit: GFZ Potsdam, 2018

## Solar wind electric field



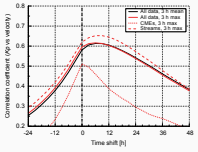



## Solar wind electric field



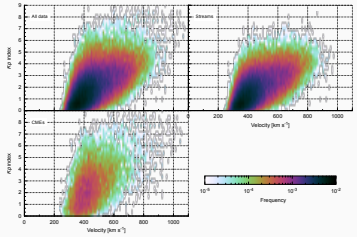



## Solar wind velocity

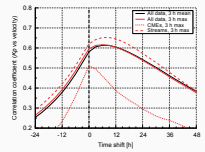





## Solar wind velocity

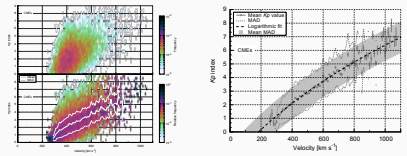




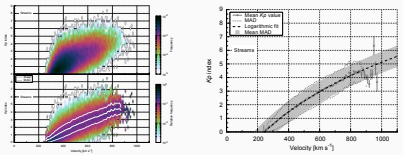



## CME velocity

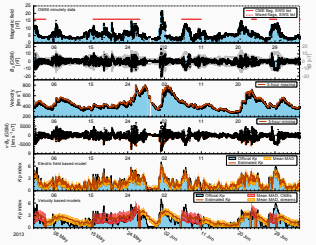




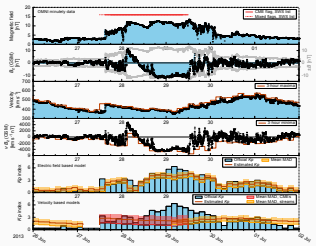

## Stream velocity










## Results

Predictive $Kp$ models based on relations with

- Solar wind electric field proxy ($vB_z$)
- Velocity of CME-associated flows ($v_{\mathrm{CME}}$)
- Velocity of solar wind streams ($v_{\mathrm{stream}}$)



## Conclusions

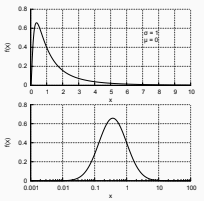
- The processing of 3-hour extrema of high time resolution data captures short-term geoeffective magnetic features that are neglected when averaging over 3-hour intervals
- The isolated treatment of CMEs and streams is beneficial to the prediction accuracy of $Kp$
- The prediction models perform well for their limited input information

→ Prediction performance





## Lognormal distribution




Probability density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}\,x}\, e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}$$

Location ($\mu$) and shape parameter ($\sigma$).

Median and average:

$$x_{\mathrm{med}} = \exp(\mu)\,, \quad x_{\mathrm{avg}} = \exp\left(\mu + \frac{\sigma^2}{2}\right)$$

$$f(x) = \frac{1}{2\sqrt{\pi \ln\left(\frac{x_{\mathrm{avg}}}{x_{\mathrm{med}}}\right)}\, x} \exp\left(-\frac{\ln^2\left(\frac{x}{x_{\mathrm{med}}}\right)}{4 \ln\left(\frac{x_{\mathrm{avg}}}{x_{\mathrm{med}}}\right)}\right)$$

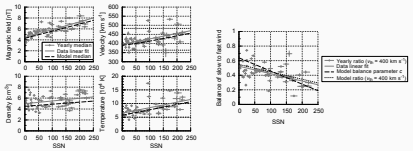


## Near-Sun region

Unsolved problems: - Coronal heating mechanisms
- Solar wind acceleration processes
- Solar energetic particle sources



## Solar activity






## PSP perihelia prediction