

# 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*

PhD student  
within the doctoral program ProPhys,  
Georg-August University School of Science  
(GAUSS)

Institute for Astrophysics  
Georg-August-Universität Göttingen

### Examination board members

Dr. Volker Bothmer (supervisor, referee)  
Prof. Dr. Ansgar Reiners (2nd referee)  
Prof. Dr. Stefan Dreizler  
Prof. Dr. Wolfram Kollatschny  
Prof. Dr. Hardi Peter  
Prof. Dr. Andreas Tilgner

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

Empirical solar wind model

# 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

# 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

# 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

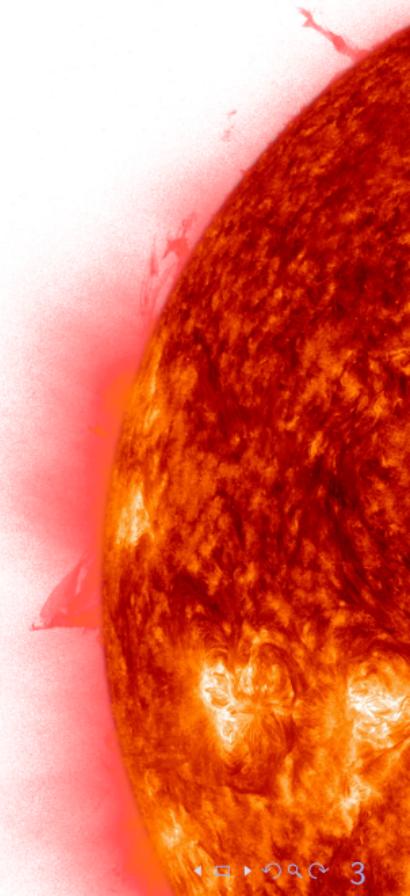
- Introduction

- Solar activity
  - Solar wind
  - Parker Solar Probe (PSP)

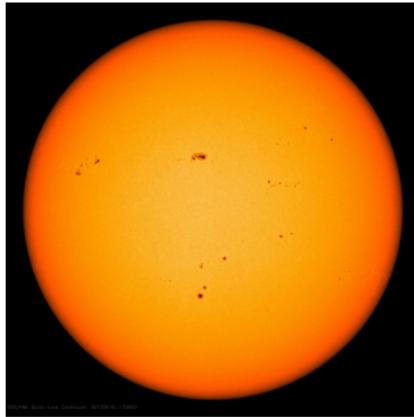
- Empirical solar wind model

- Solar wind model
  - Prediction for PSP orbit

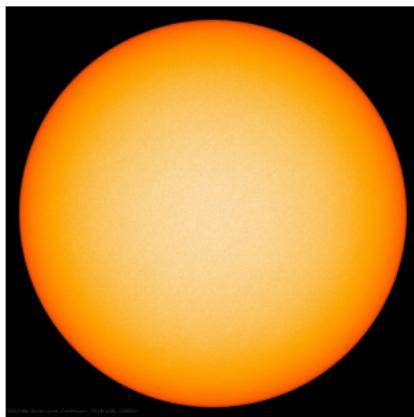
- Summary



# Solar activity

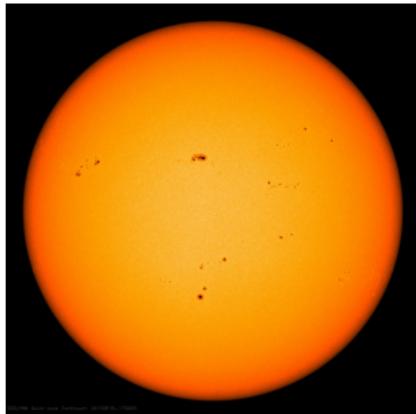


Credit: NASA SDO/HMI, 16 May 2013

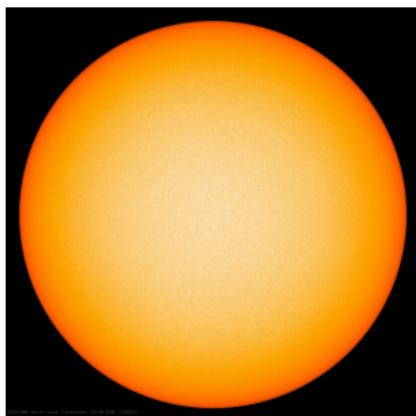


Credit: NASA SDO/HMI, 28 October 2018

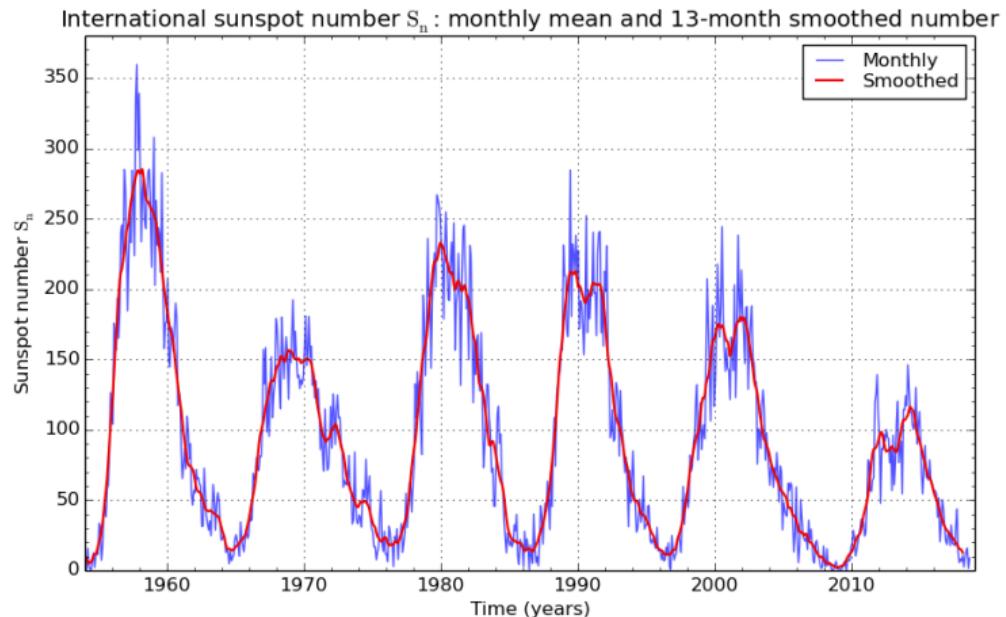
# Solar activity



Credit: NASA SDO/HMI, 16 May 2013

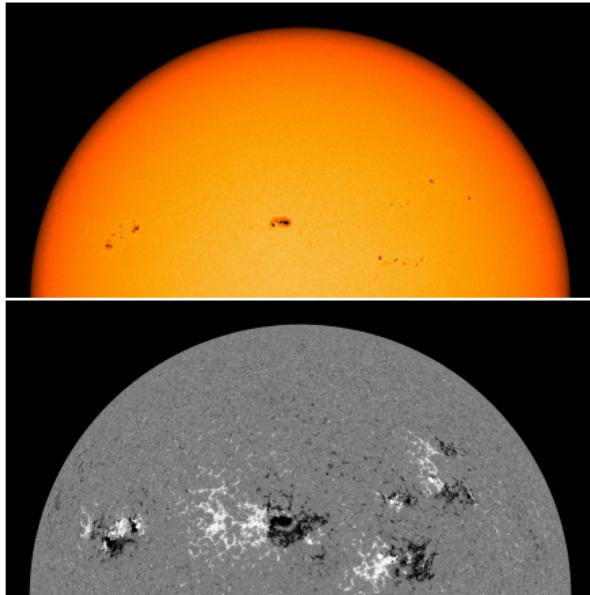


Sunspot number:  
11-year periodicity – solar cycle

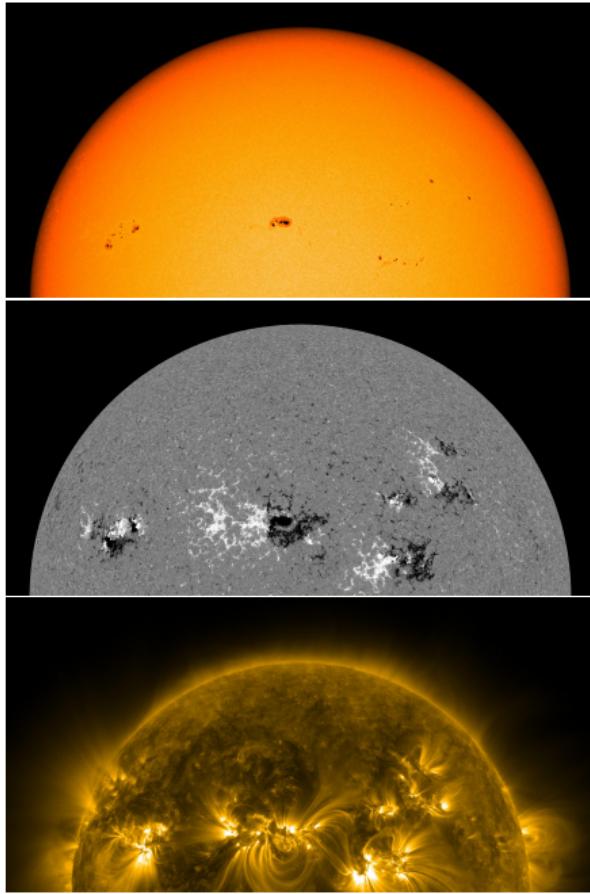


SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2018 September 1

## Solar activity

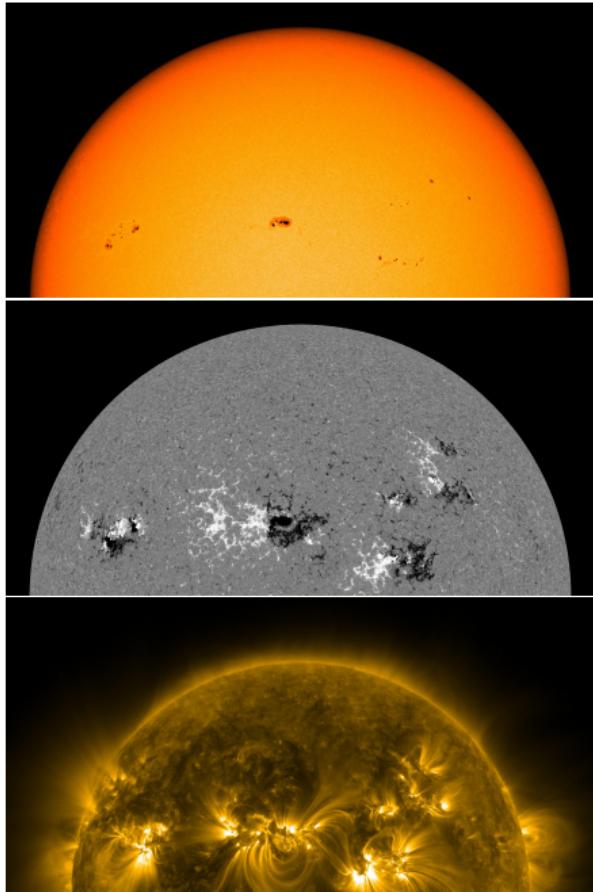


# Solar activity

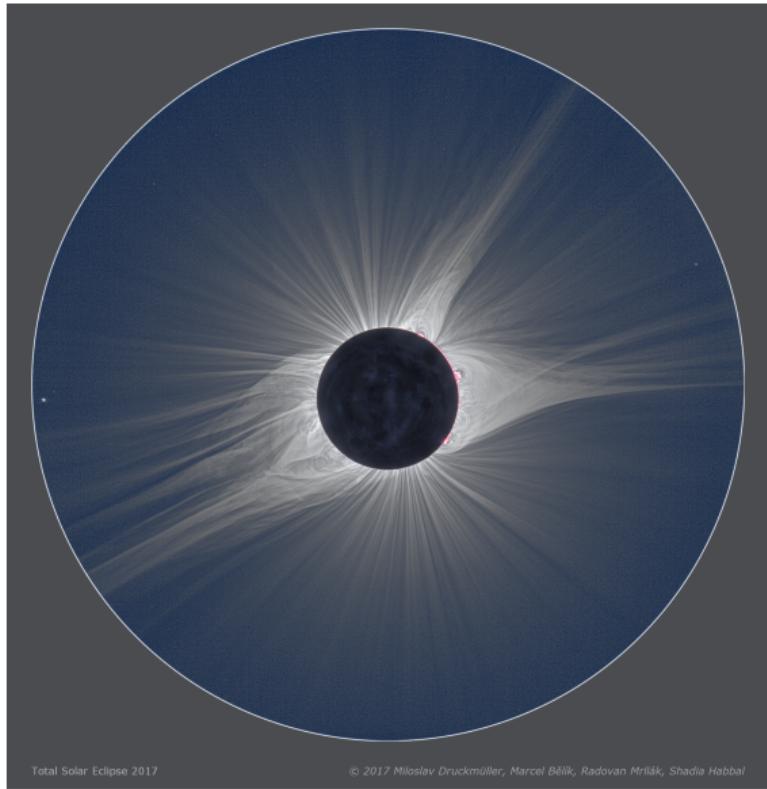


Credit: NASA SDO/HMI and SDO/AIA, 16 May 2013

# Solar activity



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



Total Solar Eclipse 2017

© 2017 Miloslav Druckmüller, Marcel Bělík, Radovan Mrallák, Shadia Habbal

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

# Solar wind

## Solar wind

- Theoretical model (Parker, 1958)
- In-situ measurements confirmed its existence in 1959
- Spacecraft monitored it continuously near Earth since

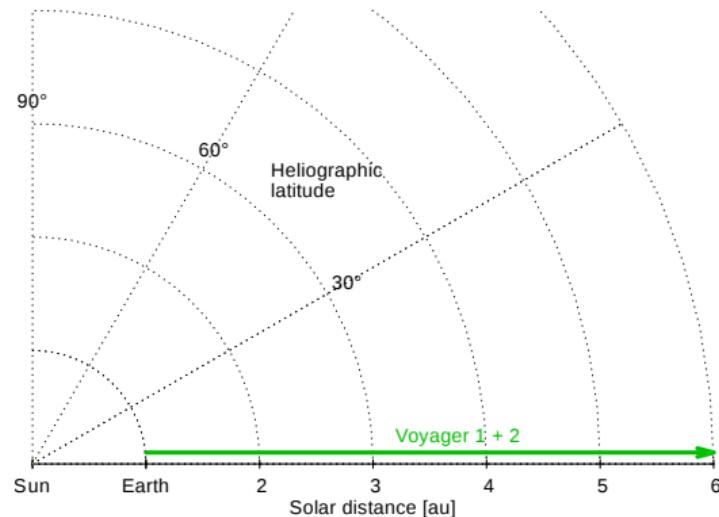
# Solar wind

## Solar wind

- Theoretical model (Parker, 1958)
- In-situ measurements confirmed its existence in 1959
- Spacecraft monitored it continuously near Earth since

Solar wind was measured in-situ throughout the heliosphere:

- Voyager 1 & 2 – out to heliopause (1–120 au)



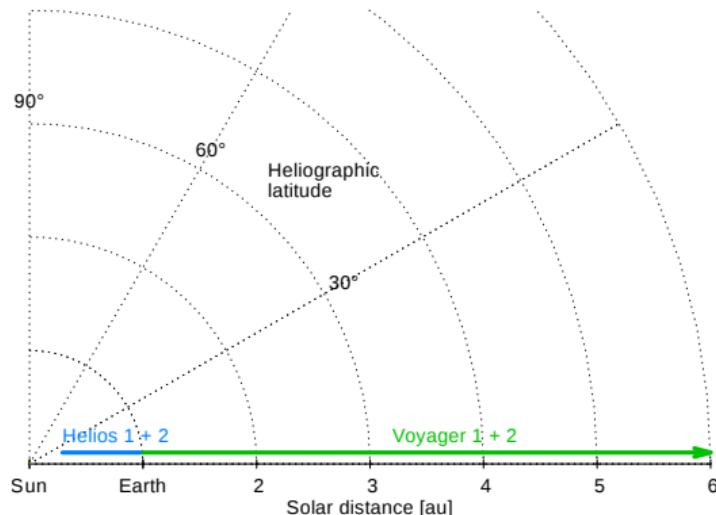
# Solar wind

## Solar wind

- Theoretical model (Parker, 1958)
- In-situ measurements confirmed its existence in 1959
- Spacecraft monitored it continuously near Earth since

Solar wind was 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)



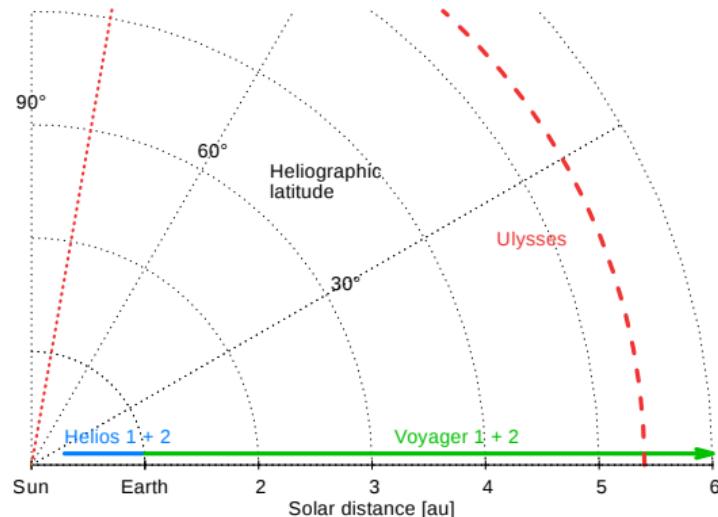
# Solar wind

## Solar wind

- Theoretical model (Parker, 1958)
- In-situ measurements confirmed its existence in 1959
- Spacecraft monitored it continuously near Earth since

Solar wind was 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 ( $\pm 79^\circ$ )



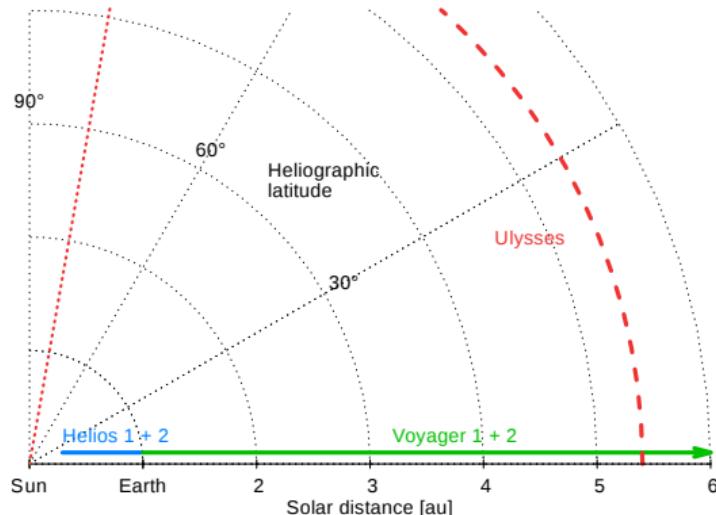
# Solar wind

## Solar wind

- Theoretical model (Parker, 1958)
- In-situ measurements confirmed its existence in 1959
- Spacecraft monitored it continuously near Earth since

Solar wind was 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 ( $\pm 79^\circ$ )



Different types of solar wind:

- slow wind streams
- fast wind streams
- coronal mass ejections

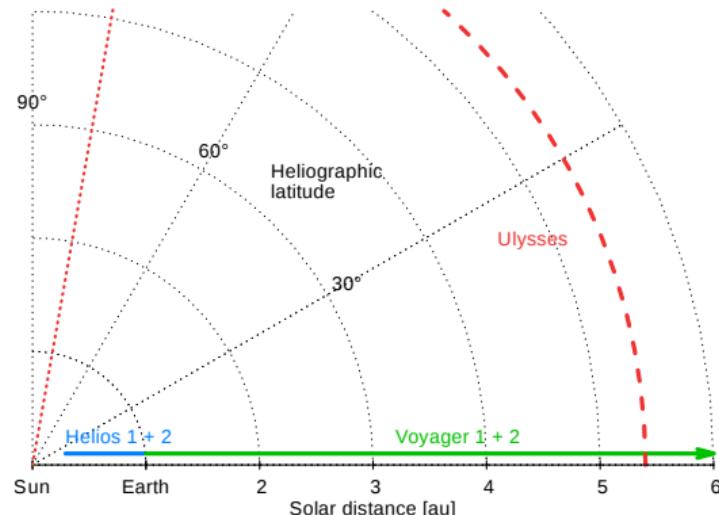
# Solar wind

## Solar wind

- Theoretical model (Parker, 1958)
- In-situ measurements confirmed its existence in 1959
- Spacecraft monitored it continuously near Earth since

Solar wind was 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 ( $\pm 79^\circ$ )



Different types of solar wind:

- slow wind streams
- fast wind streams
- coronal mass ejections

⇒ Their share varies with solar activity

# Solar wind



Total Solar Eclipse 2017

© 2017 Miloslav Druckmüller, Zuzana Druckmüllerová, Jana Hoderová, Petr Štarha, Shadia Habbal

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

The near-Sun region is of special scientific interest:

- Coronal heating
- Solar wind acceleration

# Solar wind



Total Solar Eclipse 2017

© 2017 Miloslav Druckmüller, Zuzana Druckmüllerová, Jana Hoderová, Petr Štarha, Shadia Habbal

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

The near-Sun region is of special scientific interest:

- Coronal heating
- Solar wind acceleration

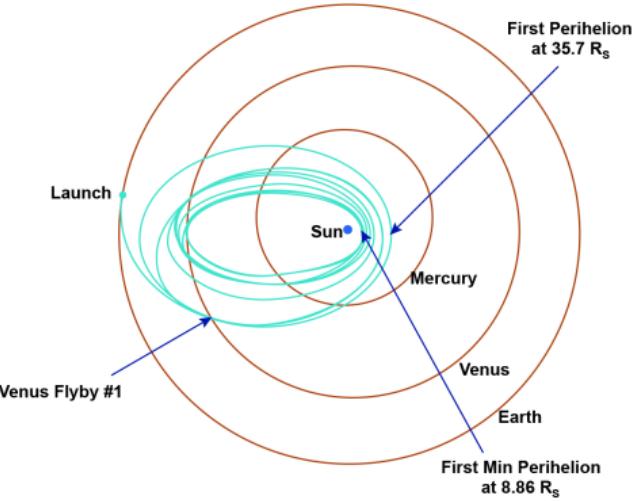
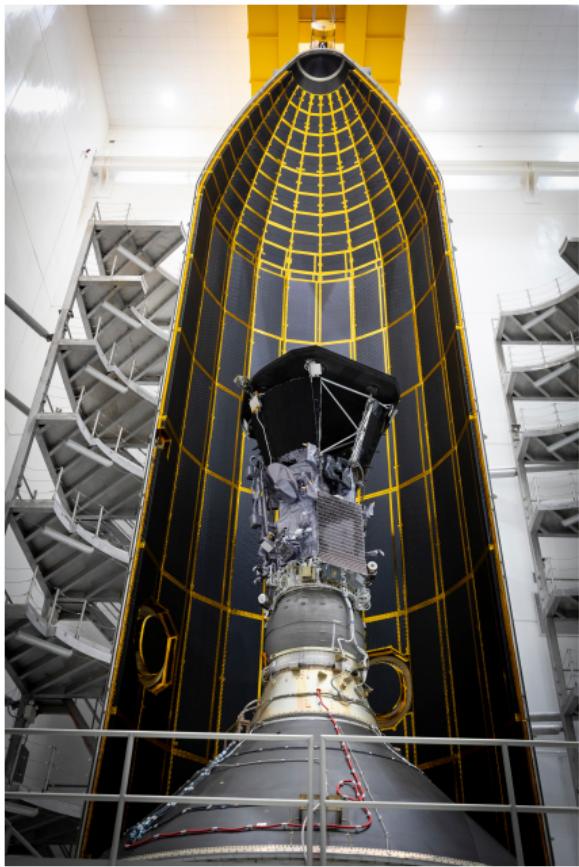
The Parker Solar Probe mission is to fly within  $10 R_{\odot}$  of the Sun  
(Fox et al., 2015)

# Parker Solar Probe



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

# Parker Solar Probe



Credit: NASA/Johns Hopkins APL, 2018

Launch

1st Venus flyby

1st perihelion at  $36.7 R_\odot$

...

22nd perihelion at  $9.86 R_\odot$

12 August 2018

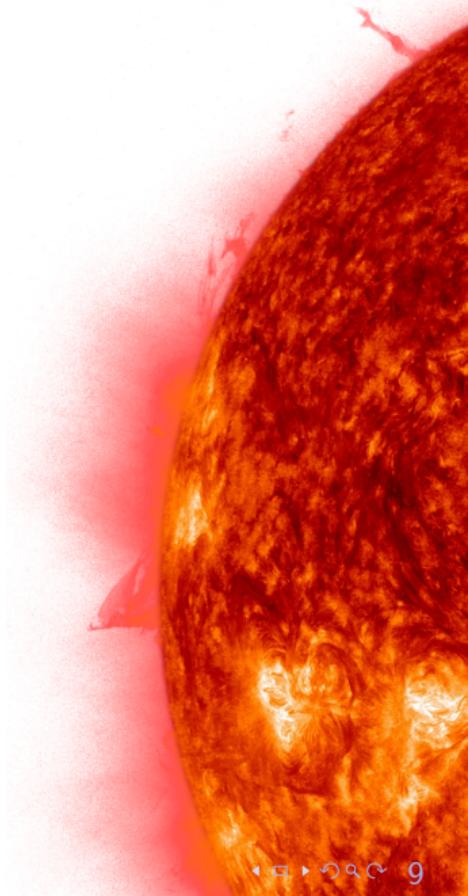
3 October

6 November

...

24 December 2024

- Introduction
  - Solar activity
  - Solar wind
  - Parker Solar Probe (PSP)
- Empirical solar wind model
  - Solar wind model
  - Prediction for PSP orbit
- Summary



# Empirical solar wind model

The aim of this study is to predict the solar wind environment for the PSP orbit

## Concept of the model:

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

# Empirical solar wind model

The aim of this study is to predict the solar wind environment for the PSP orbit

## Concept of the model:

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

## Solar wind environment (key parameters)

- Magnetic field strength
- Velocity
- Density
- Temperature

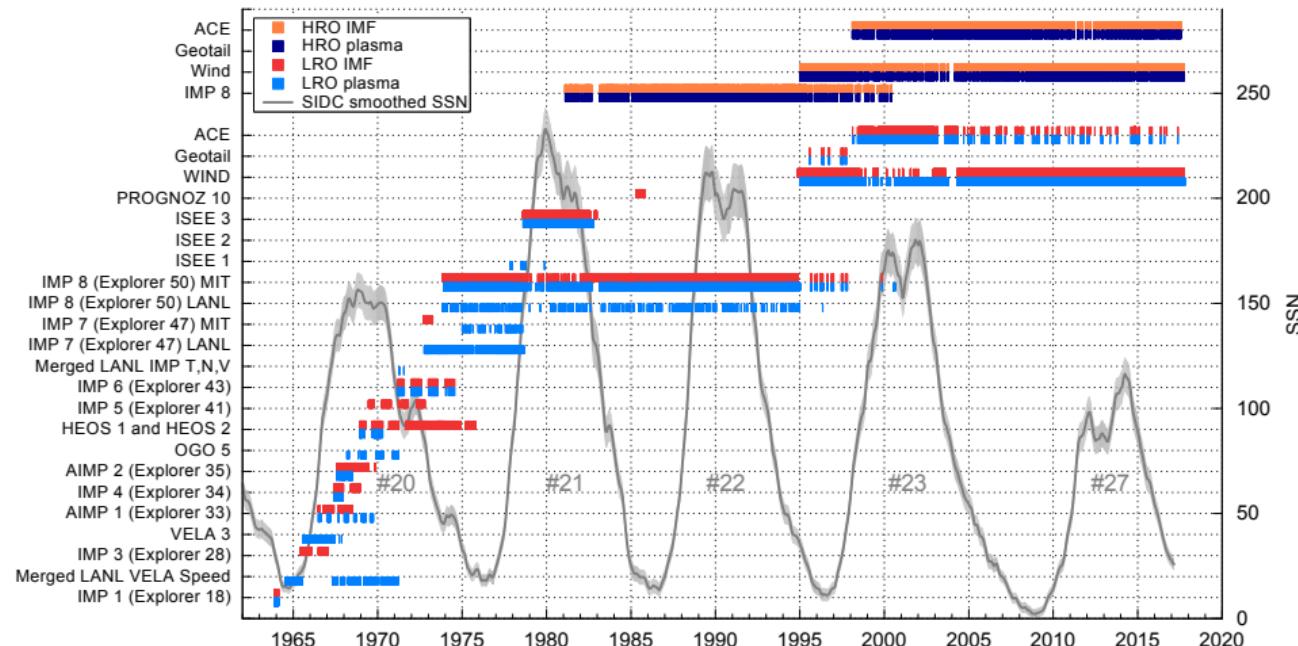
## Uniqueness of the model:

- Solar wind parameters are represented by frequency distributions instead of average values
- These are shifted with solar activity and solar distance

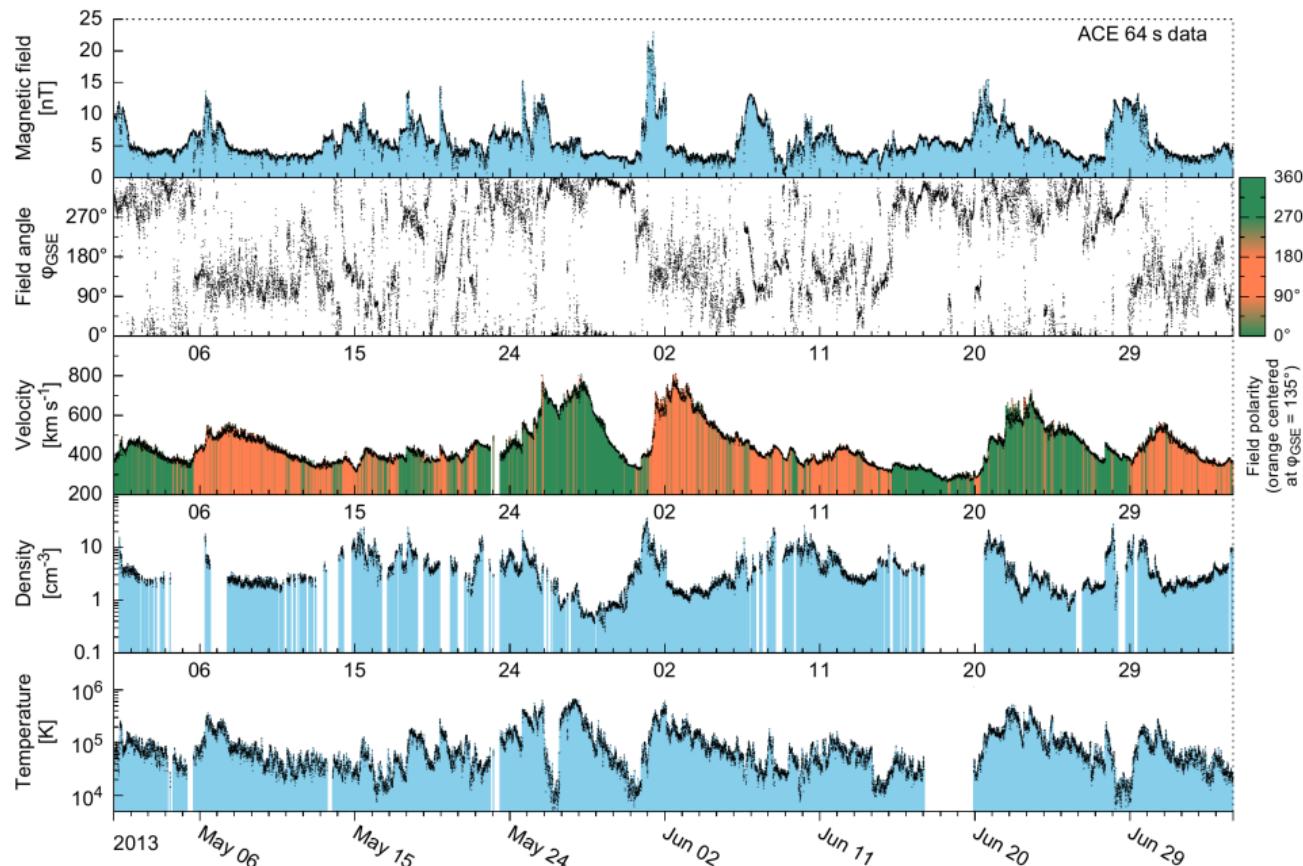
# Solar wind data

OMNI data set (King & Papitashvili, 2005)

- intercalibrated multi-spacecraft data
- low-resolution data since 1963; high-resolution data since 1981



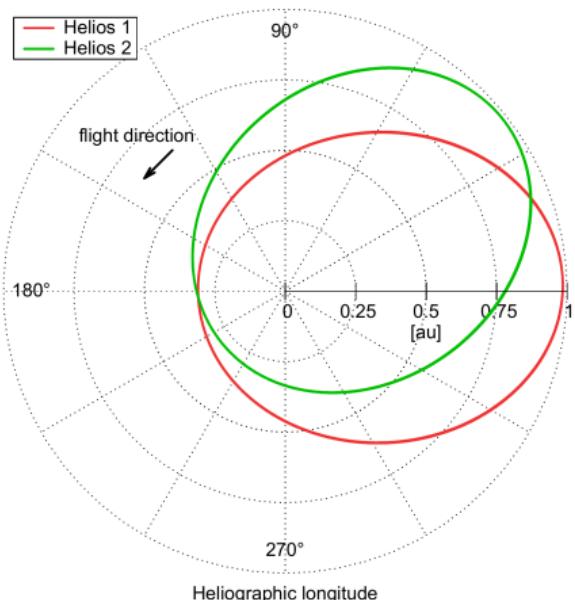
# Solar wind



# Solar wind data

Helios data set (Rosenbauer et al., 1977)

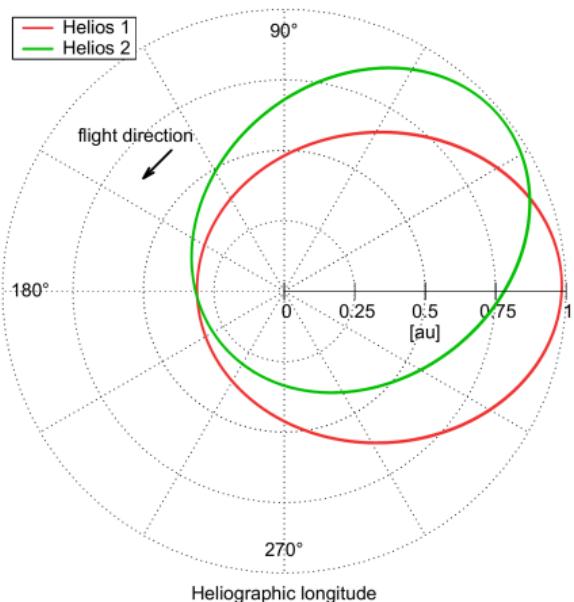
- Helios 1 and Helios 2 probes
- operated between 1974–1981
- solar distance range 0.29–0.98 au



# Solar wind data

Helios data set (Rosenbauer et al., 1977)

- Helios 1 and Helios 2 probes
- operated between 1974–1981
- solar distance range 0.29–0.98 au

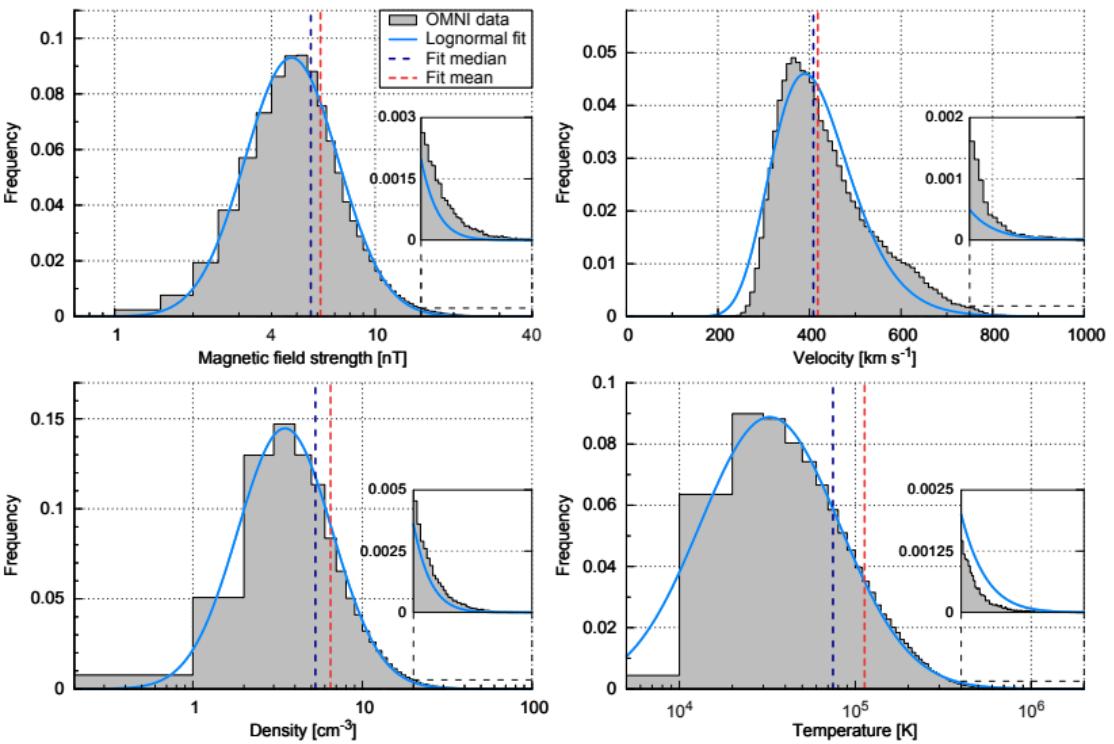


## Solar wind model data use

- 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 – OMNI data

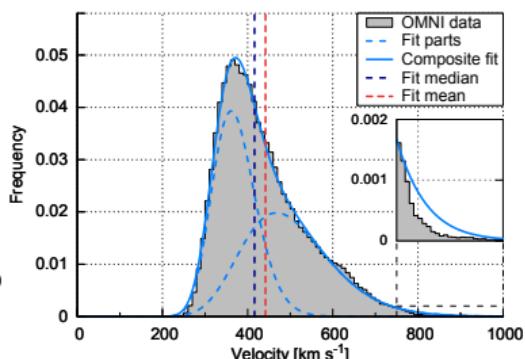
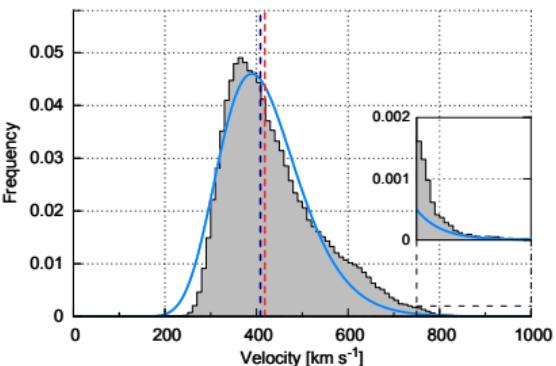
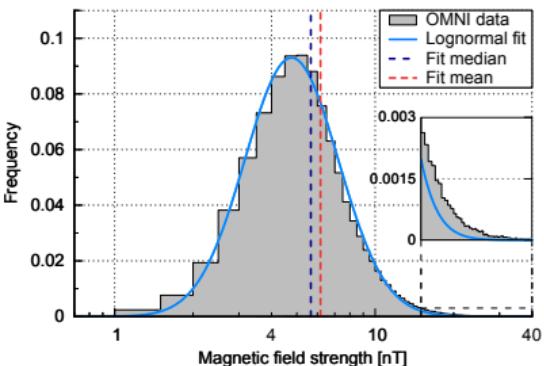
Hourly OMNI data from 1963 to 2016



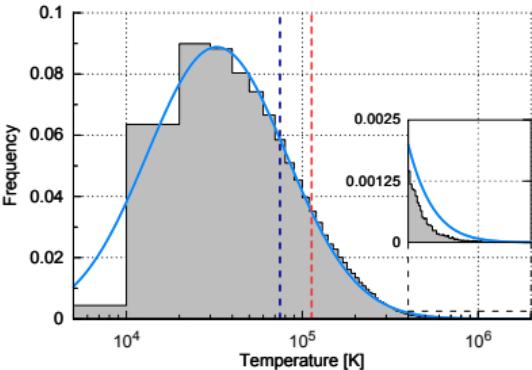
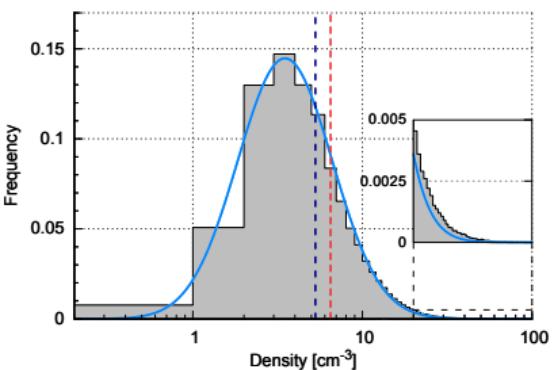
Credit: Venzmer & Bothmer (2018)

# Frequency distributions – OMNI data

Hourly OMNI data from 1963 to 2016



Credit: Venzmer & Bothmer (2018)

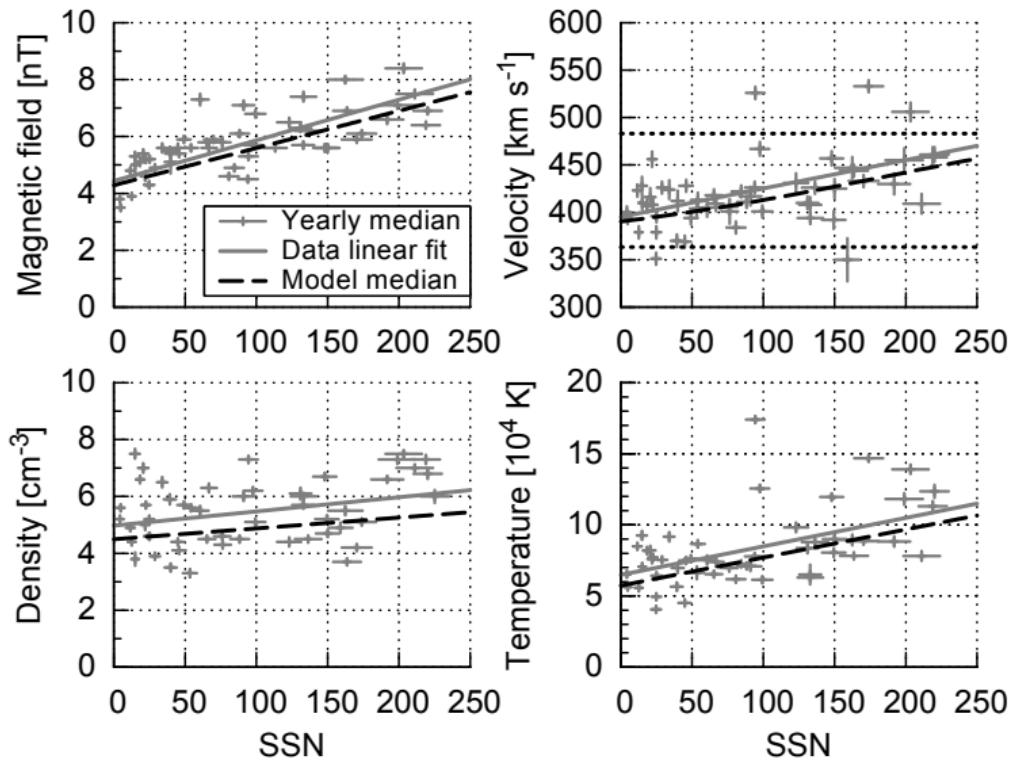


Credit: Venzmer & Bothmer (2018)

Note: Lognormal functions are fully described by their median and mean values

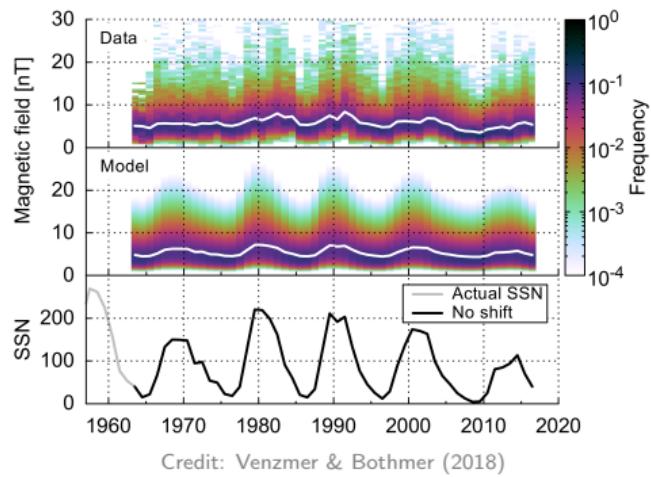
# Solar activity dependence – OMNI data

Linear relations with the SSN:



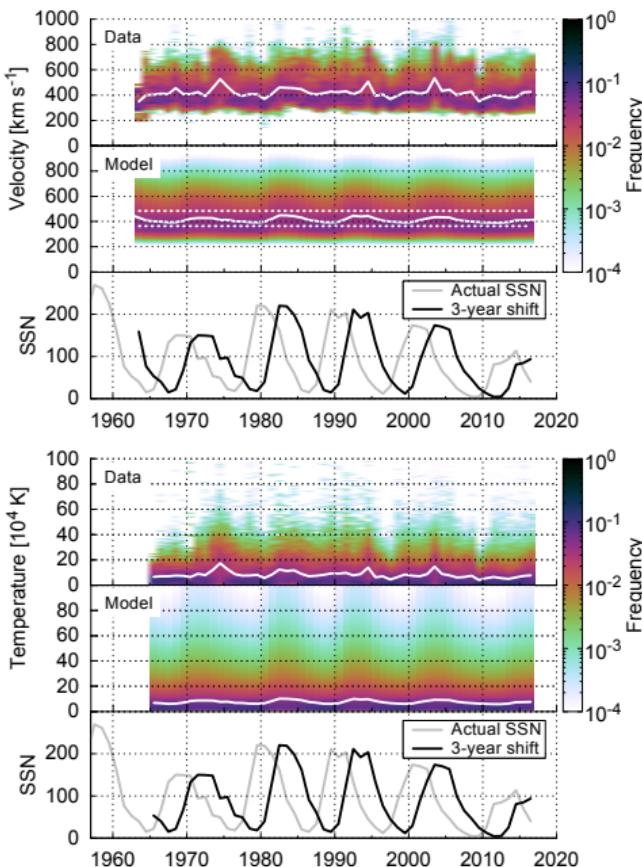
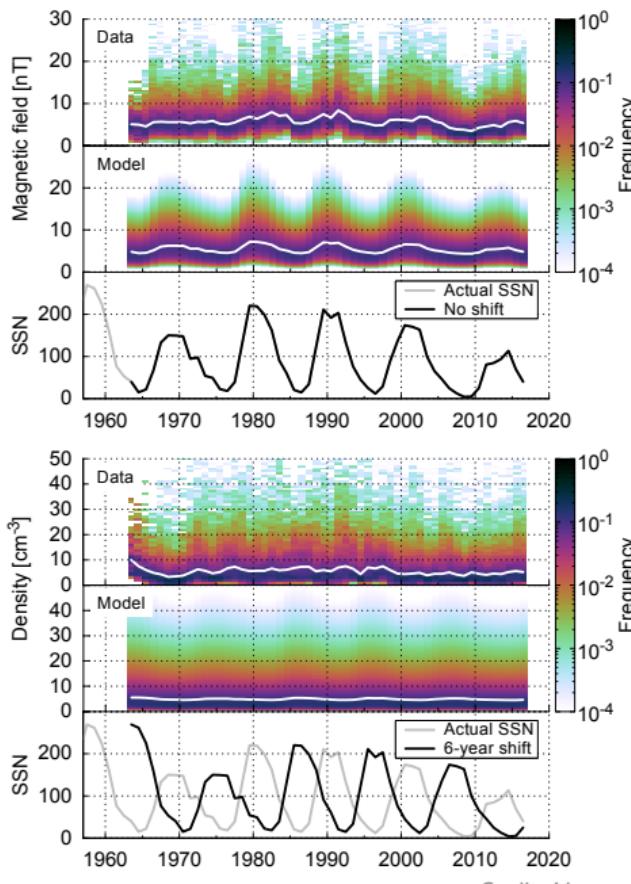
Credit: Venzmer & Bothmer (2018)

# Solar activity dependence – OMNI data



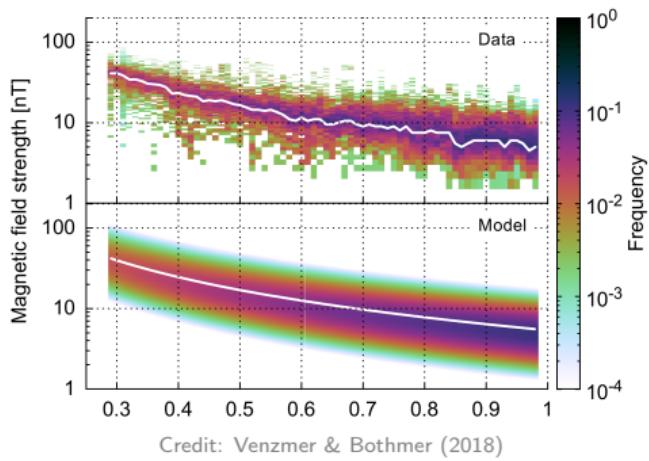
Credit: Venzmer & Bothmer (2018)

# Solar activity dependence – OMNI data



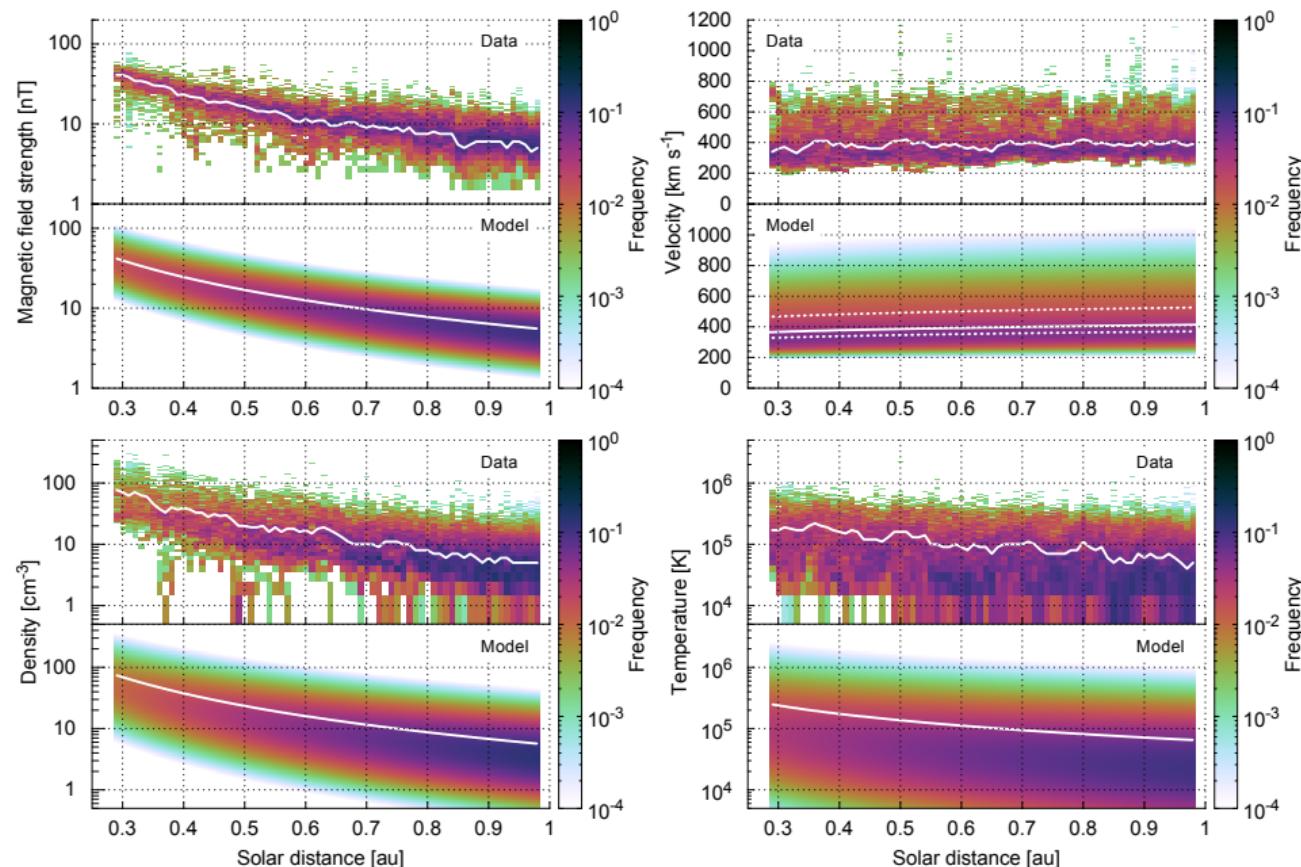
Credit: Venzmer & Bothmer (2018)

# Solar distance dependence – Helios data



Credit: Venzmer & Bothmer (2018)

# Solar distance dependence – Helios data



Credit: Venzmer & Bothmer (2018)

## Final model

The actual models combine:

- frequency distributions  
 $W(x_{\text{med}}, x_{\text{avg}})$
- median and mean values  
 $x_{\text{med}}(ssn, r), x_{\text{avg}}(ssn, r)$
- solar activity and distance  
are time dependent  
 $ssn(t + t_{\text{lag}}), r(t)$

# Final model

## Relations for the median and mean values

The actual models combine:

- frequency distributions  
 $W(x_{\text{med}}, x_{\text{avg}})$
- median and mean values  
 $x_{\text{med}}(ssn, r), x_{\text{avg}}(ssn, r)$
- solar activity and distance  
are time dependent  
 $ssn(t + t_{\text{lag}}), r(t)$

Magnetic field strength

$$B_{\text{med}}^{\text{Parker}}(ssn, r) = (0.0131 \text{ nT} \cdot ssn + 4.29 \text{ nT}) \cdot \sqrt{(r^{-1.858})^2 + (r^{-1.32})^2}$$

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

Velocity

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

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

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

Density

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

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

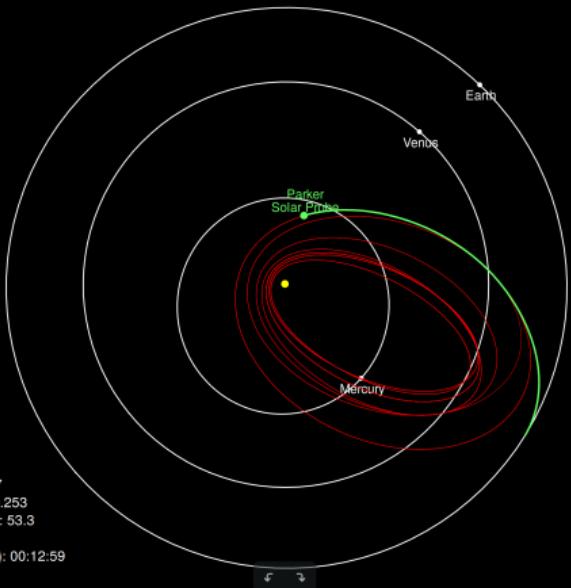
Temperature

$$T_{\text{med}}(ssn, r) = (197 \text{ K} \cdot ssn + 5.73 \times 10^4 \text{ K}) \cdot r^{-1.10}$$

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

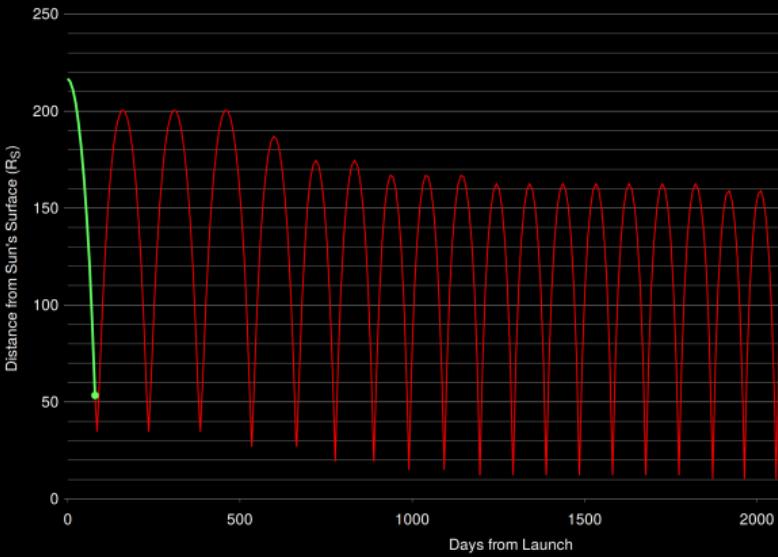
# Prediction for PSP orbit

Parker Solar Probe Mission Trajectory and Current Position



Credit: NASA

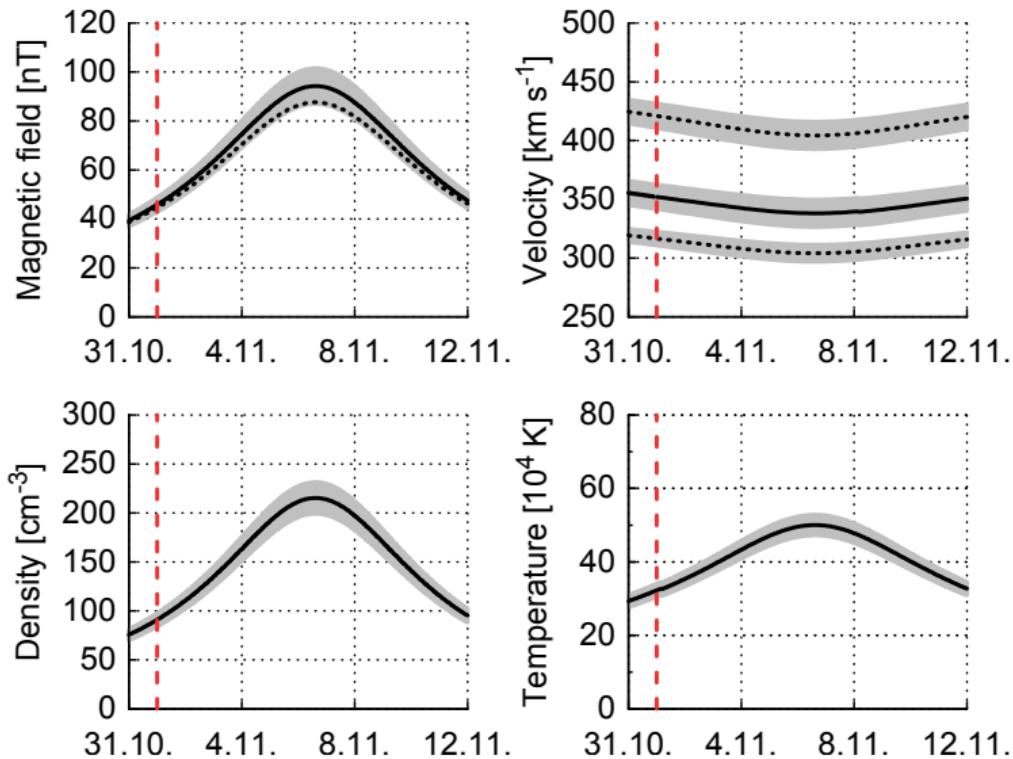
Parker Solar Probe Distance from Sun



- ⇒ Extrapolate the model in distance
- ⇒ Feed the model with SSN predictions

# Prediction for PSP orbit

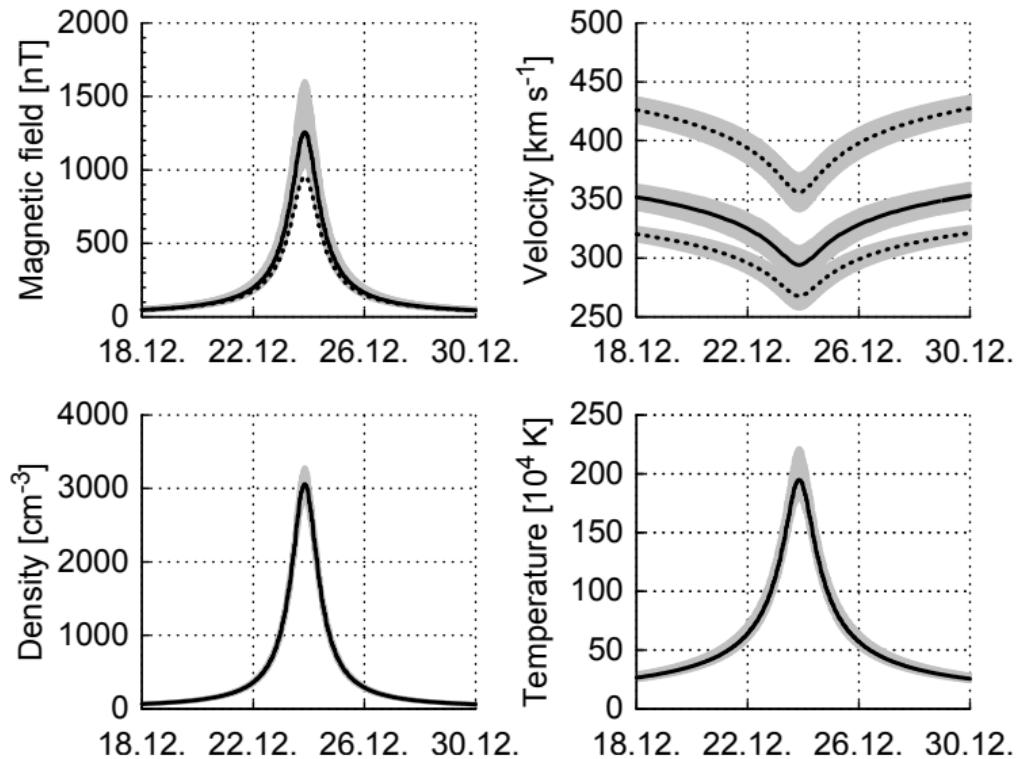
Perihelion #1 at  $36.7 R_{\odot}$



November 2018

# Prediction for PSP orbit

Perihelion #22 at  $9.86 R_{\odot}$



## Comparison with other studies

### Predicted values at $9.86 R_{\odot}$

$$B = 1241 \text{ nT}$$

$$v = 290 \text{ km s}^{-1}$$

$$n = 2951 \text{ cm}^{-3}$$

$$T = 1.93 \times 10^6 \text{ K}$$

## Comparison with other studies

### Predicted values at $9.86 R_{\odot}$

$$B = 1241 \text{ nT}$$

$$v = 290 \text{ km s}^{-1}$$

$$n = 2951 \text{ cm}^{-3}$$

$$T = 1.93 \times 10^6 \text{ K}$$

- Predicted magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)

## Comparison with other studies

### Predicted values at $9.86 R_{\odot}$

$$B = 1241 \text{ nT}$$

$$v = 290 \text{ km s}^{-1}$$

$$n = 2951 \text{ cm}^{-3}$$

$$T = 1.93 \times 10^6 \text{ K}$$

- Predicted magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)
- Remote observations reveal slow solar wind with velocities of  $200 \text{ km s}^{-1}$  at  $10 R_{\odot}$  (Sheeley et al., 1997; Wang et al., 2000)

## Comparison with other studies

### Predicted values at $9.86 R_{\odot}$

$$B = 1241 \text{ nT}$$

$$v = 290 \text{ km s}^{-1}$$

$$n = 2951 \text{ cm}^{-3}$$

$$T = 1.93 \times 10^6 \text{ K}$$

- Predicted magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)
- Remote observations reveal slow solar wind with velocities of  $200 \text{ km s}^{-1}$  at  $10 R_{\odot}$  (Sheeley et al., 1997; Wang et al., 2000)
- Predicted density values agree well with radio burst observations (Leblanc et al., 1998)

## Comparison with other studies

### Predicted values at $9.86 R_{\odot}$

$$B = 1241 \text{ nT}$$

$$v = 290 \text{ km s}^{-1}$$

$$n = 2951 \text{ cm}^{-3}$$

$$T = 1.93 \times 10^6 \text{ K}$$

- Predicted magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)
- Remote observations reveal slow solar wind with velocities of  $200 \text{ km s}^{-1}$  at  $10 R_{\odot}$  (Sheeley et al., 1997; Wang et al., 2000)
- Predicted density values agree well with radio burst observations (Leblanc et al., 1998)
- Near-Sun ( $1\text{--}2 R_{\odot}$ ) coronal temperatures are at 2–3 MK (Billings, 1959; Liebenberg et al., 1975)

## Comparison with other studies

### Predicted values at $9.86 R_{\odot}$

$$B = 1241 \text{ nT}$$

$$v = 290 \text{ km s}^{-1}$$

$$n = 2951 \text{ cm}^{-3}$$

$$T = 1.93 \times 10^6 \text{ K}$$

- Predicted magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)
- Remote observations reveal slow solar wind with velocities of  $200 \text{ km s}^{-1}$  at  $10 R_{\odot}$  (Sheeley et al., 1997; Wang et al., 2000)
- Predicted density values agree well with radio burst observations (Leblanc et al., 1998)
- Near-Sun ( $1-2 R_{\odot}$ ) coronal temperatures are at 2–3 MK (Billings, 1959; Liebenberg et al., 1975)

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

- Remote observations show the limits of the extrapolation
- Predicted 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

# Summary

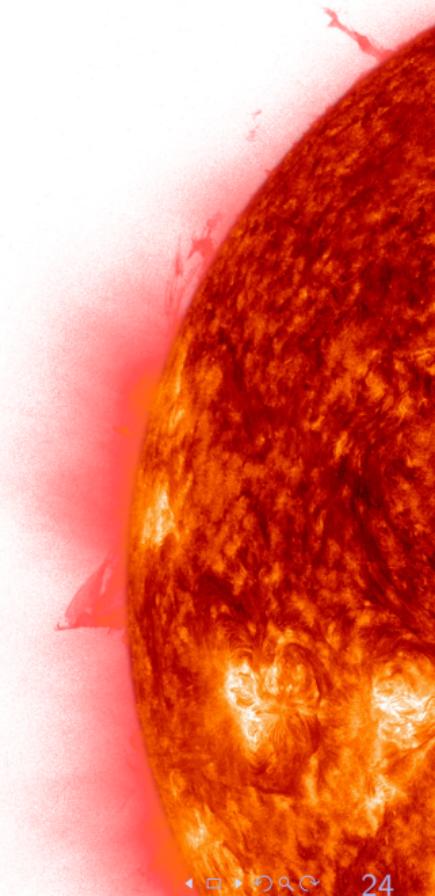
- I derived an empirical solar wind model for the inner heliosphere.  
It considers:
  - frequency distributions of the key solar wind parameters
    - magnetic field strength
    - velocity
    - density
    - temperature
  - solar activity via the sunspot number
  - solar distance
- The model is extrapolated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

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

## Outlook

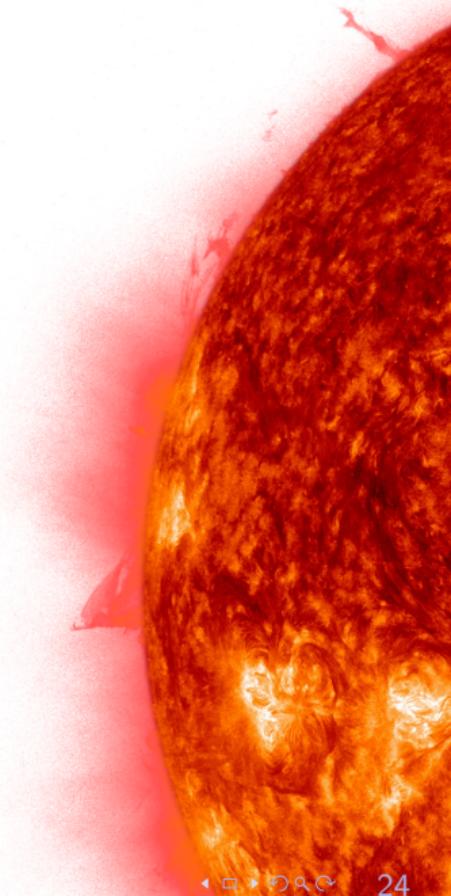
- Possible modifications to model (e.g., flux conservation)
- Refine model with additional solar wind data from Mercury probes and the upcoming Solar Orbiter mission
- The predictions can be used as a reference for the first measurements made by PSP
- The PSP measurements can be used to validate the extrapolations



## 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
- The predictions can be used as a reference for the first measurements made by PSP
- The PSP measurements can be used to validate the extrapolations

Thank you!



# References |

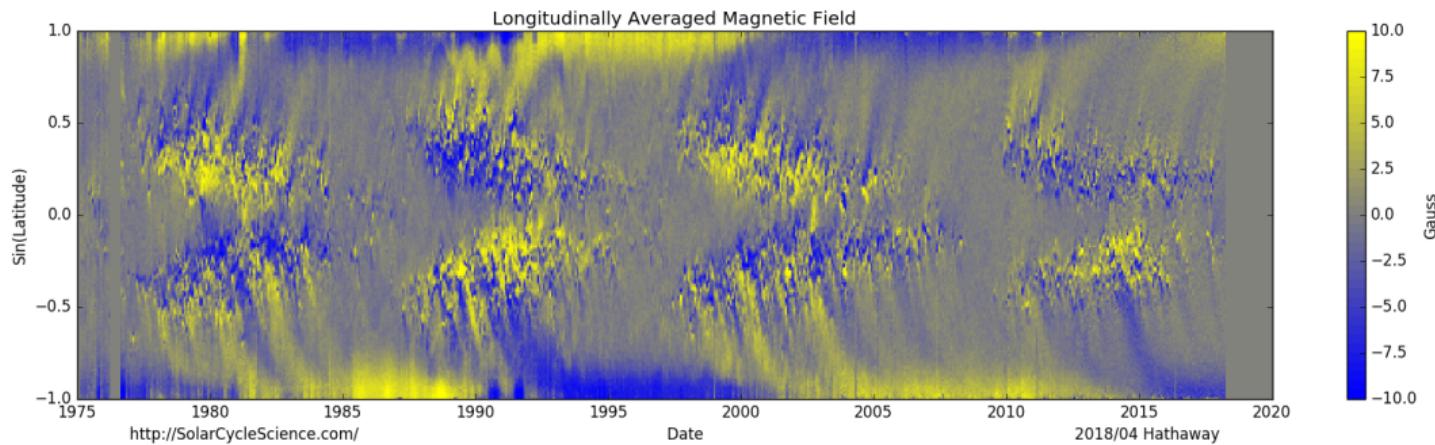
- Banaszkiewicz, M., Axford, W. I. & McKenzie, J. F. 1998, *An analytic solar magnetic field model*, Astron. Astrophys., 337, 940, [ADS].
- Billings, D. E. 1959, *Distribution of Matter with Temperature in the Emission Corona.*, Astrophys. J., 130, 961, [DOI], [ADS].
- Bothmer, V. & Schwenn, R. 1998, *The structure and origin of magnetic clouds in the solar wind*, Annales Geophysicae, 16, 1, [DOI], [ADS].
- Cranmer, S. R. & van Ballegooijen, A. A. 2005, *On the Generation, Propagation, and Reflection of Alfvén Waves from the Solar Photosphere to the Distant Heliosphere*, Astrophys. J., Suppl. Ser., 156, 265, [DOI], [ADS].
- Davies, K. 1990, *Ionospheric Radio* (Institution of Engineering and Technology), [link], [DOI].
- Fox, N. J., Velli, M. C., Bale, S. D. et al. 2015, *The Solar Probe Plus Mission: Humanity's First Visit to Our Star*, Space Sci. Rev., [DOI], [ADS].
- Hathaway, D. H. 2015, *The Solar Cycle*, Living Reviews in Solar Physics, 12, 4, [DOI], [ADS].
- Hughes, W. J. 1995, *Chapter 9: The magnetopause, magnetotail, and magnetic reconnection*, ed. M. Kivelson & C. Russell, Introduction to Space Physics (Cambridge University Press, Cambridge), 227–287, [ADS].
- Leblanc, Y., Dulk, G. A., & Bougeret, J.-L. 1998, Solar Phys., 183, 165
- Liebenberg, D. H., Bessey, R. J. & Watson, B. 1975, *Coronal emission line profile observations at total solar eclipses. II - 30 May 1965 results, deconvolution and interpretation*, Solar Phys., 44, 345, [DOI], [ADS].
- King, J. H. & Papitashvili, N. E. 2005, *Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data*, Journal of Geophysical Research (Space Physics), 110, 2104, [DOI], [ADS].
- Marubashi, K. & Lepping, R. P. 2007, *Long-duration magnetic clouds: a comparison of analyses using torus- and cylinder-shaped flux rope models*, Annales Geophysicae, 25, 2453, [DOI], [ADS].
- McComas, D. J., Ebert, R. W., Elliott, H. A. et al. 2008a, *Weaker solar wind from the polar coronal holes and the whole Sun*, Geophys. Res. Lett., 35, L18103, [DOI], [ADS].
- Owens, M. J. & Forsyth, R. J. 2013, *The Heliospheric Magnetic Field*, Living Reviews in Solar Physics, 10, 5, [DOI], [ADS].
- Parker, E. N. 1958, *Dynamics of the Interplanetary Gas and Magnetic Fields.*, Astrophys. J., 128, 664, [DOI], [ADS].
- Pizzo, V. J. 1991, *The evolution of corotating stream fronts near the ecliptic plane in the inner solar system. II - Three-dimensional tilted-dipole fronts*, J. Geophys. Res., 96, 5405, [DOI], [ADS].

# References II

- Rosenbauer, H., Schwenn, R., Marsch, E. et al. 1977, *A survey on initial results of the HELIOS plasma experiment*, Journal of Geophysics Zeitschrift Geophysik, 42, 561, [ADS].
- Schatten, K. H., Wilcox, J. M. & Ness, N. F. 1969, *A model of interplanetary and coronal magnetic fields*, Solar Phys., 6, 442, [DOI], [ADS].
- Sheeley, N. R., Wang, Y.-M., Hawley, S. H., et al. 1997, *Astrophys. J.*, 484, 472
- Venzmer, M. S. & Bothmer, V. 2018, *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*, Astron. Astrophys., 611, A36, [DOI], [ADS].
- 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].

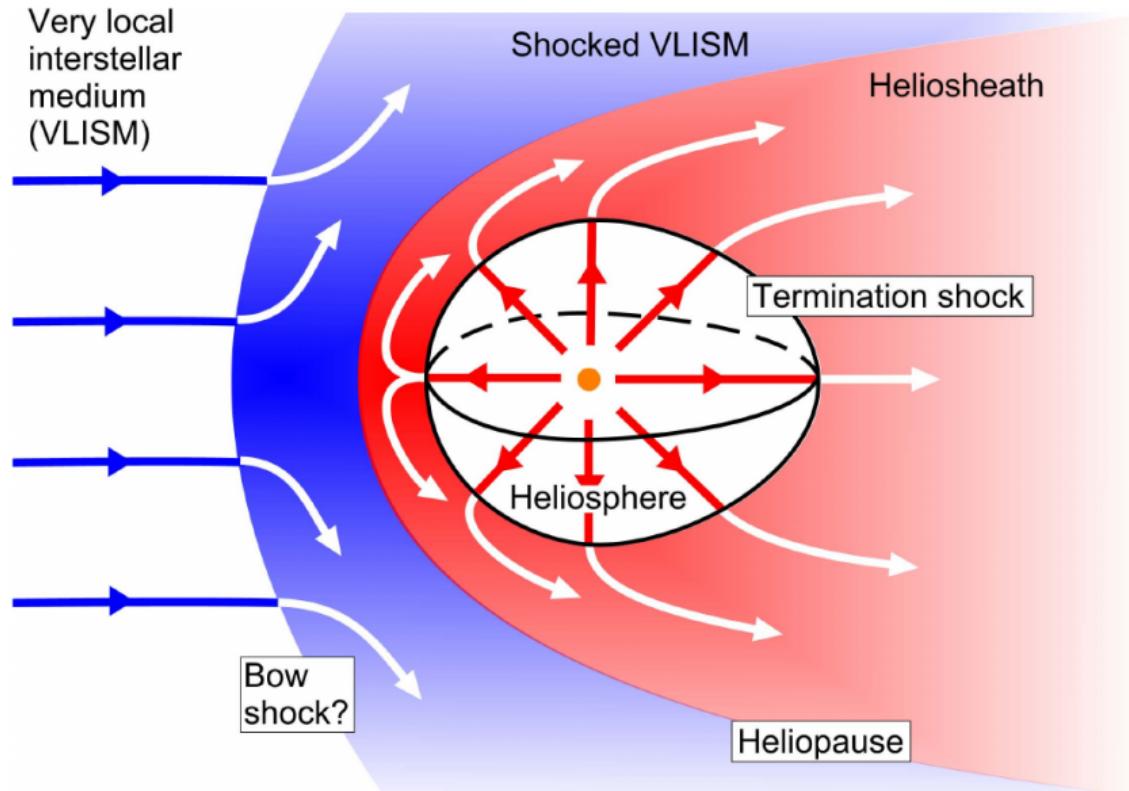
# Solar activity

## Magnetic butterfly diagram



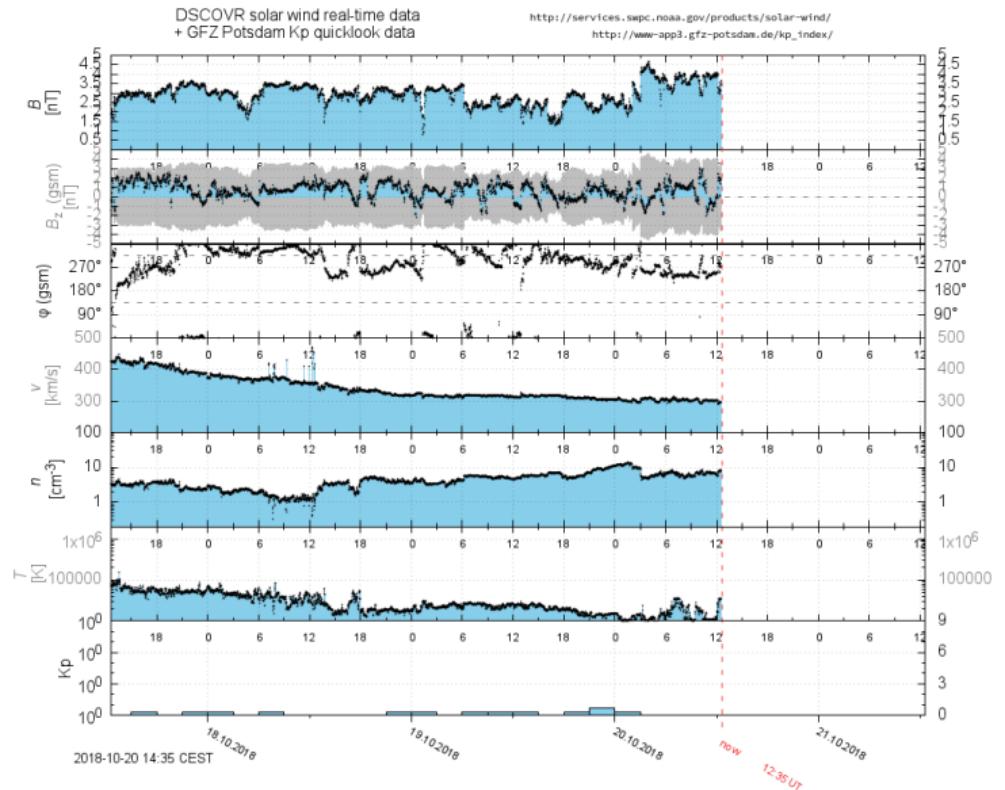
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

# Solar wind



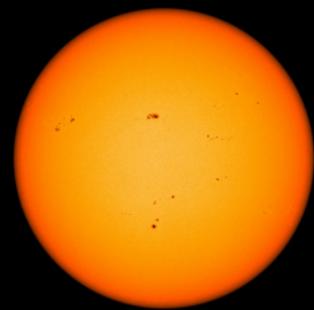
Credit: Owens & Forsyth (2013, Fig. 9)

# Solar wind

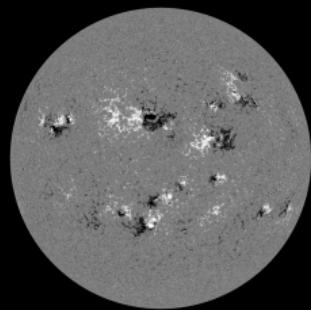


# Solar surface and atmosphere

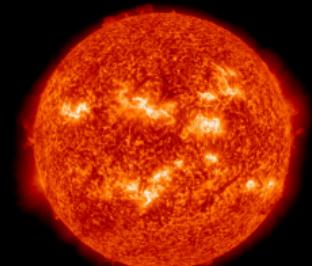
Intensitygram



Magnetogram



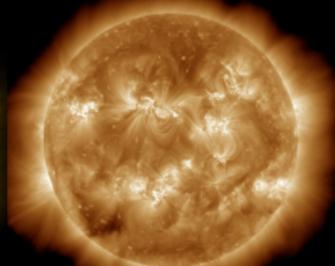
304 Å



171 Å

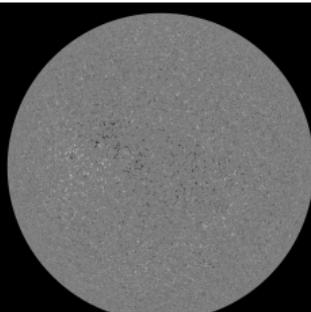
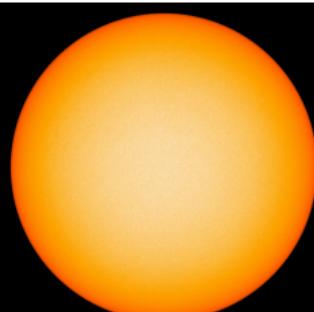


193 Å



Credit: NASA SDO/HMI, 16 May 2013

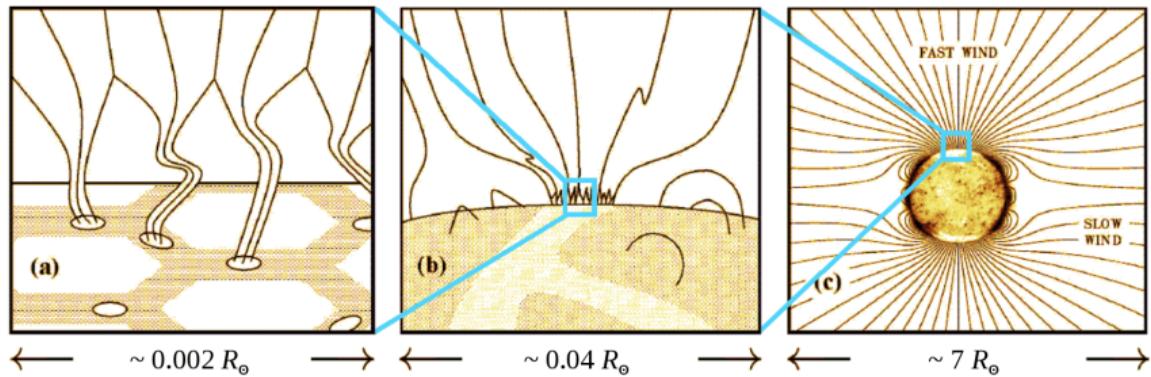
Credit: NASA SDO/AIA, 16 May 2013



304/65 304 2018-10-28 11:09:16 UT

Credit: NASA SDO/AIA, 28 October 2018

# Solar magnetic field

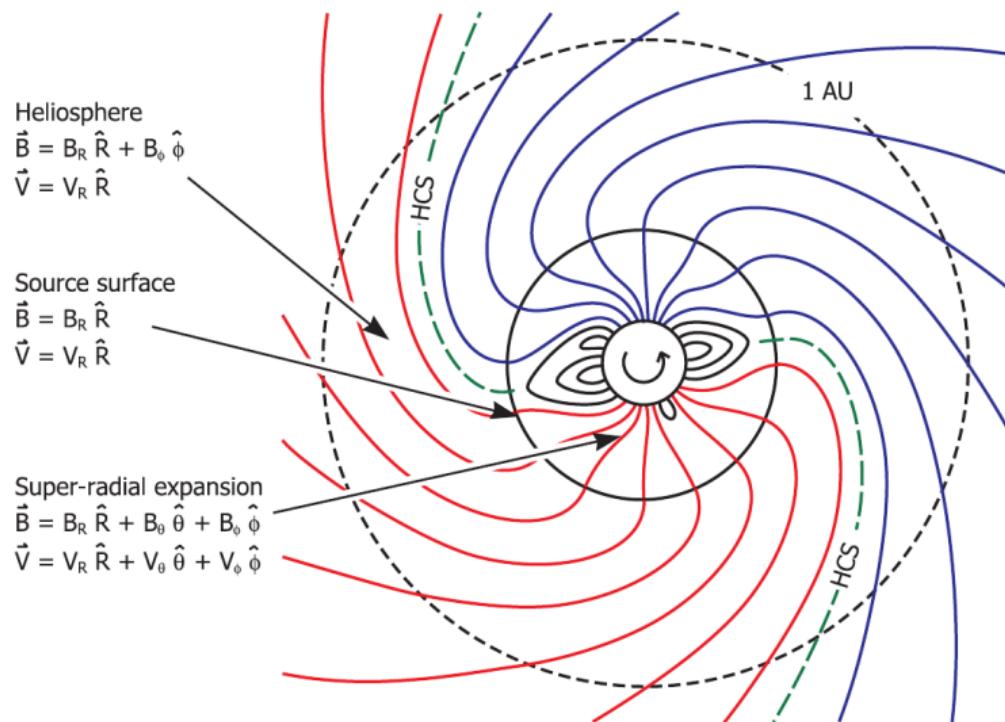


Courtesy of S. R. Cranmer

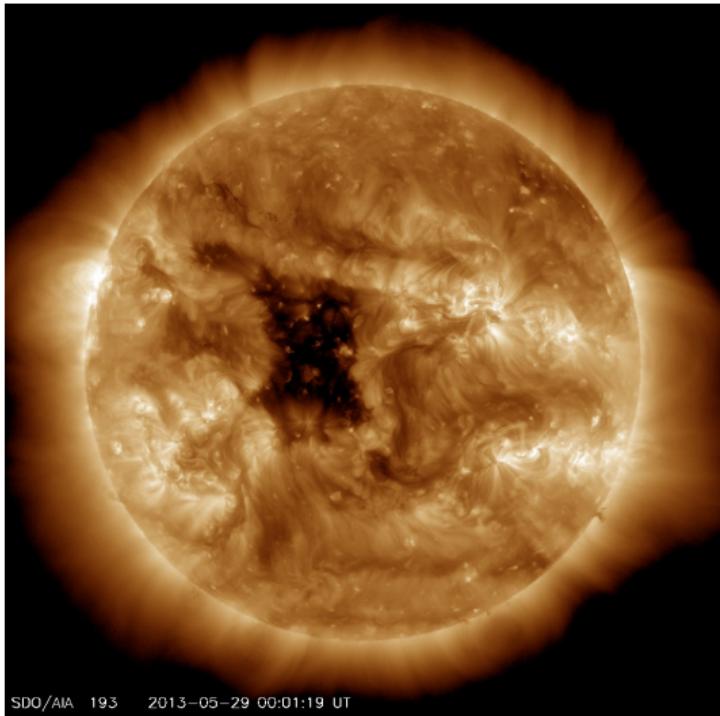
# Solar magnetic field

Theoretical model (Parker, 1958)

- Expanding isothermal solar atmosphere
- Parker spiral field geometry



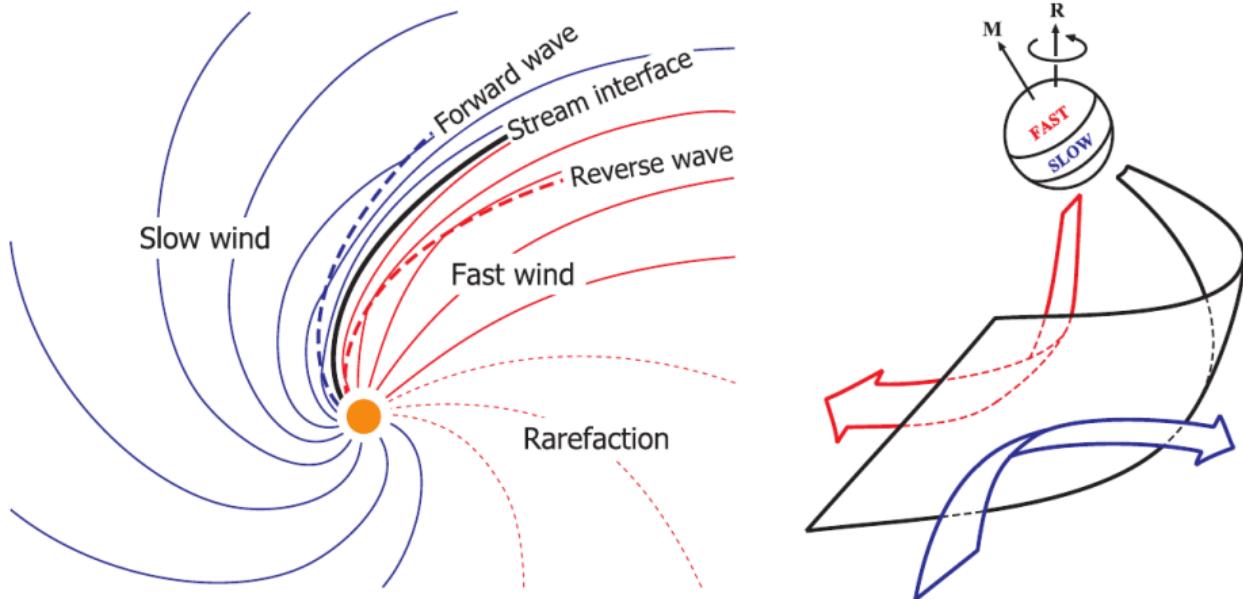
# Slow and fast solar wind



SDO/AIA 193 2013-05-29 00:01:19 UT

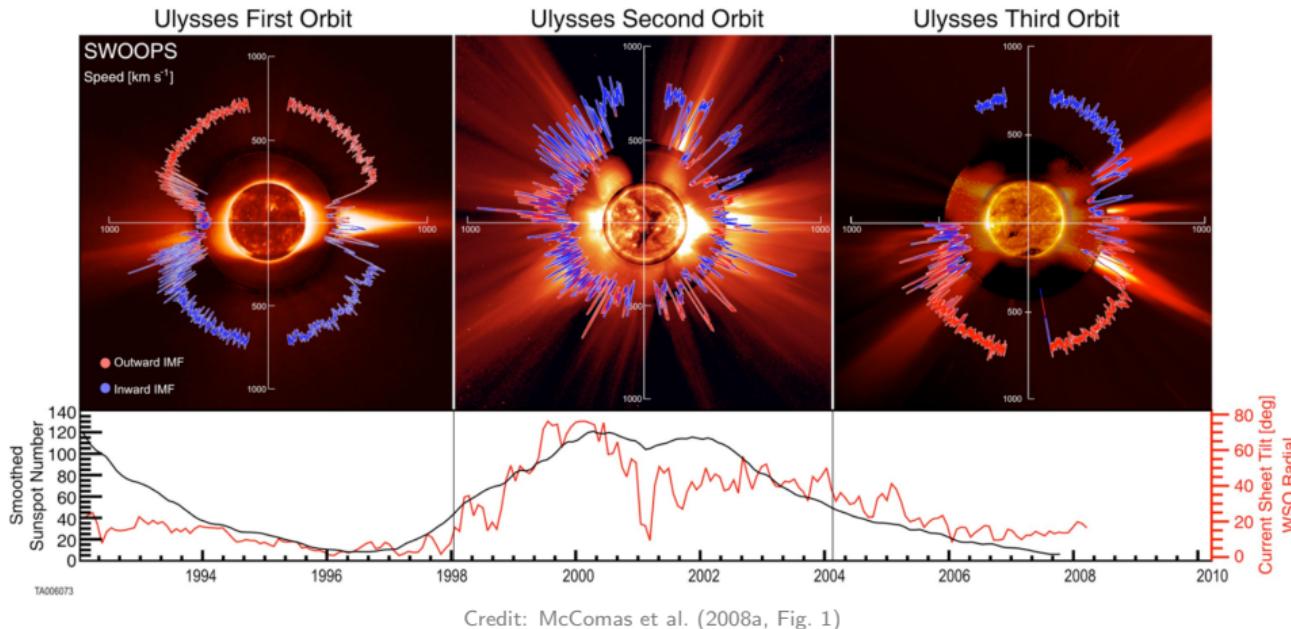
Credit: NASA/SDO and the AIA, EVE and HMI science teams

# Slow and fast solar wind



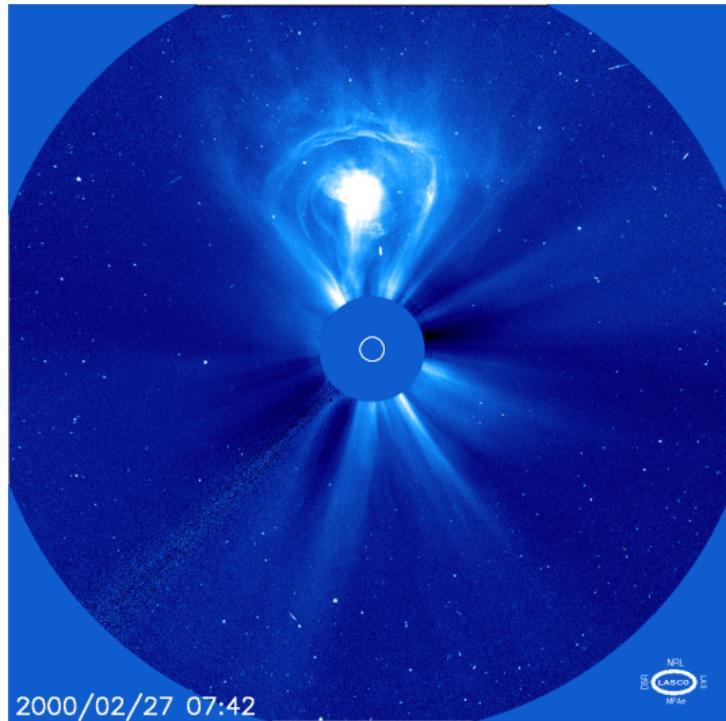
Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

# Solar activity



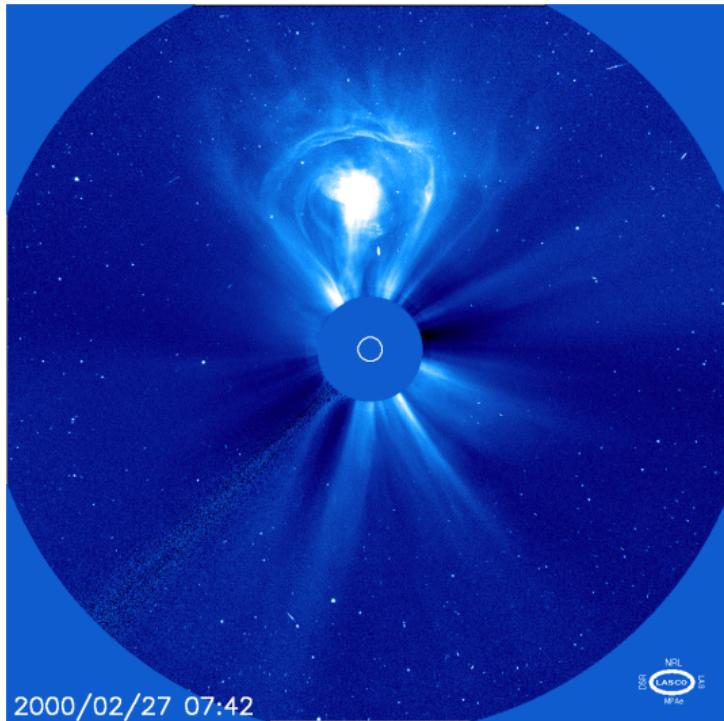
Credit: McComas et al. (2008a, Fig. 1)

# Coronal mass ejections

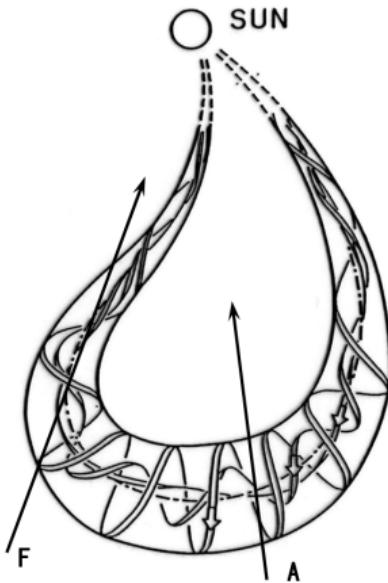


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

# Coronal mass ejections

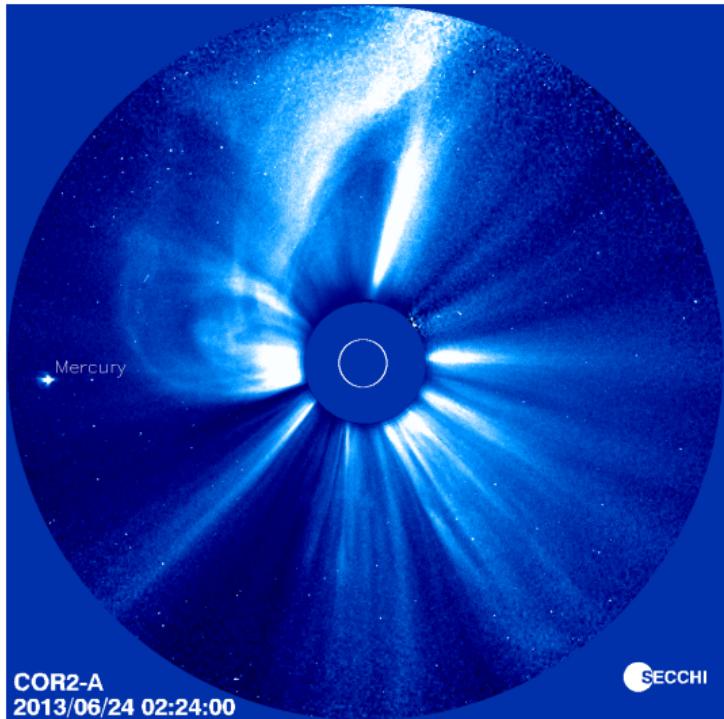


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

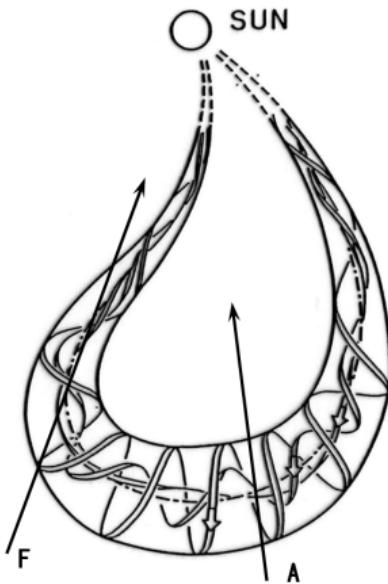


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# Coronal mass ejections

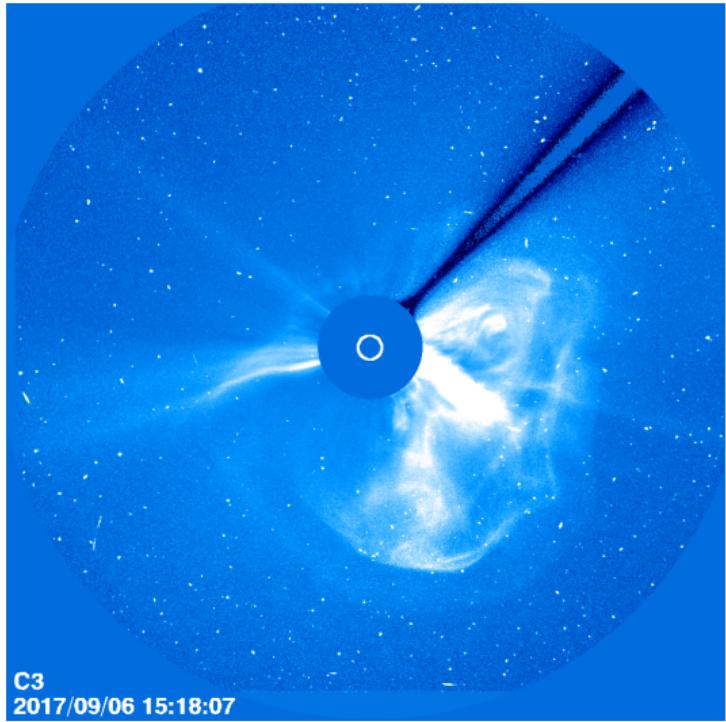


Courtesy of STEREO/COR2 consortium (NASA)



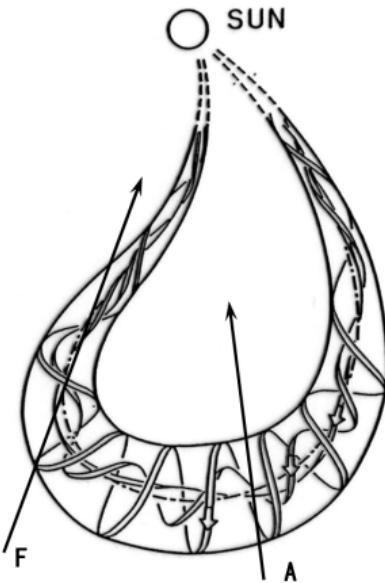
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# Coronal mass ejections



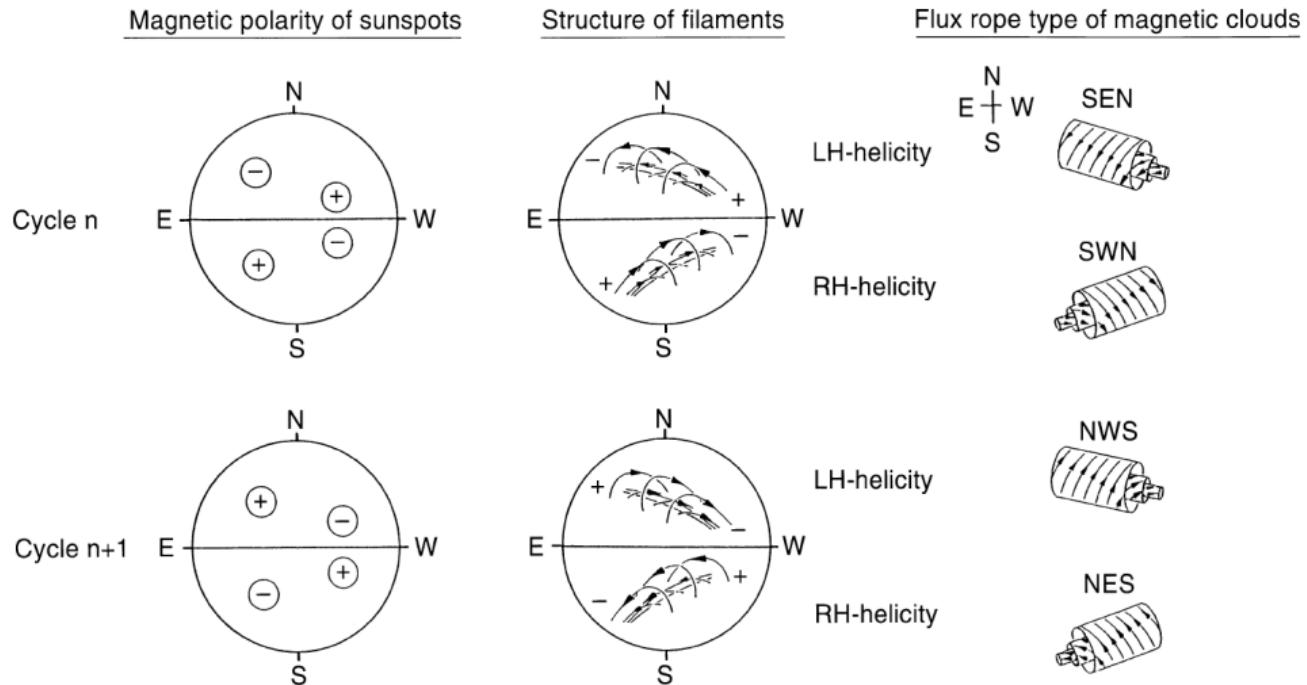
C3  
2017/09/06 15:18:07

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



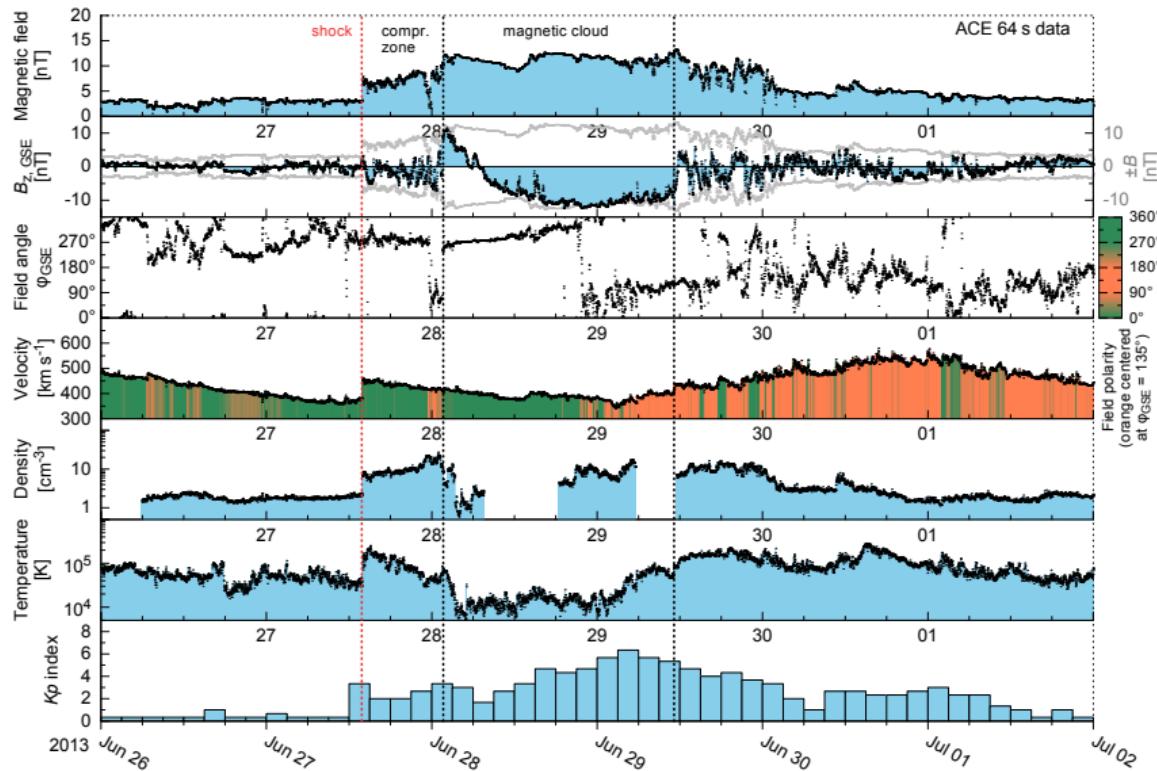
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# CME orientation

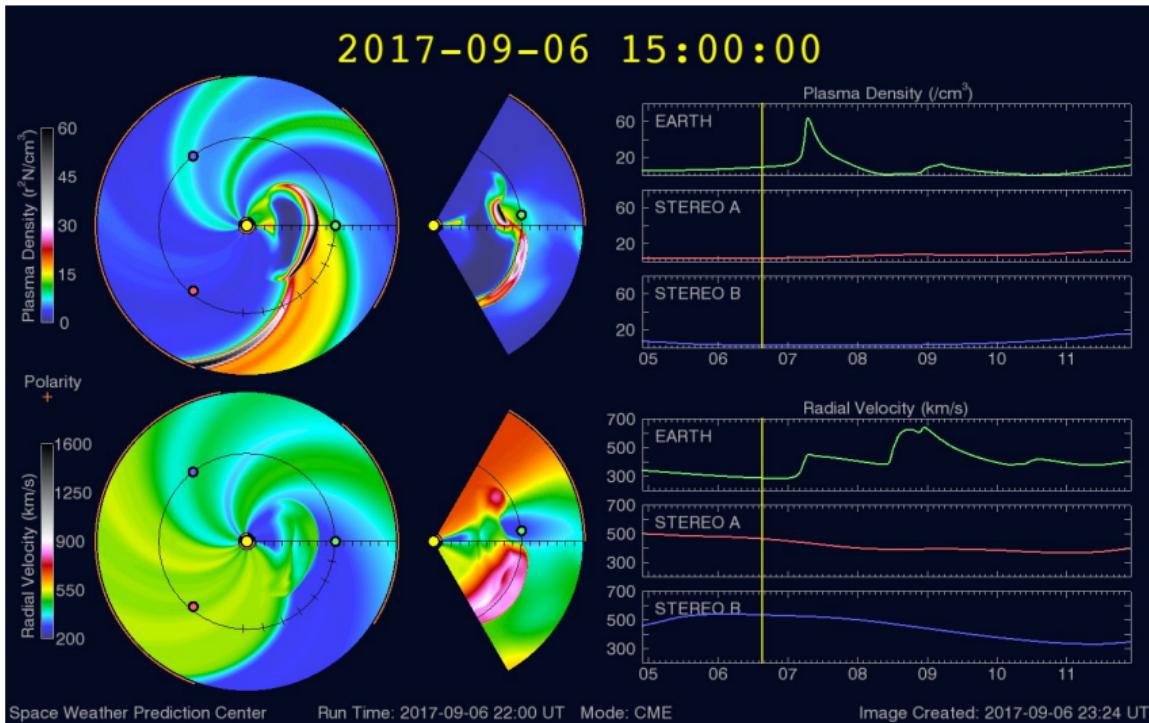


Credit: Bothmer & Schwenn (1998, Fig. 18)

# In-situ CMEs

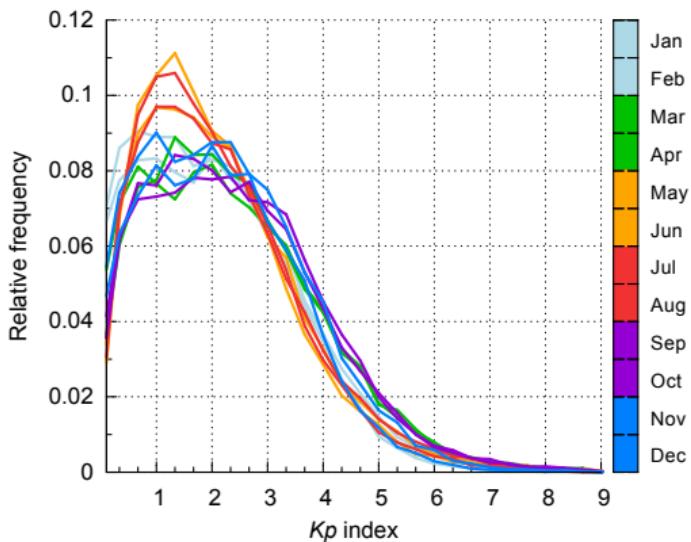
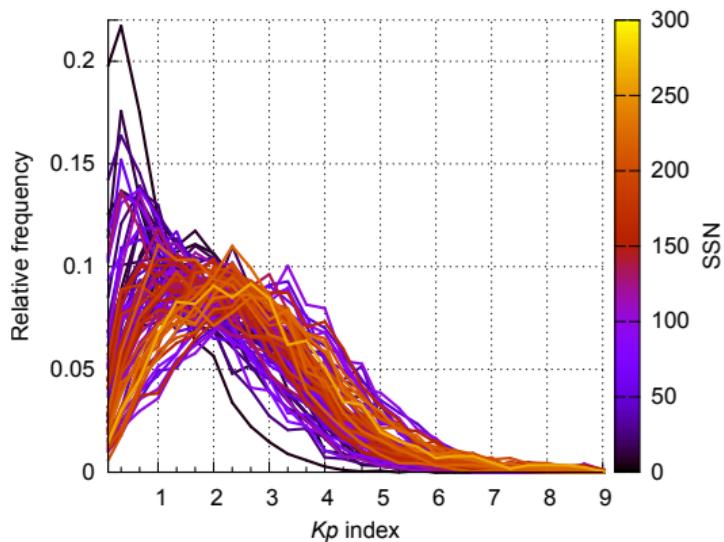


# Solar wind and CME forecast

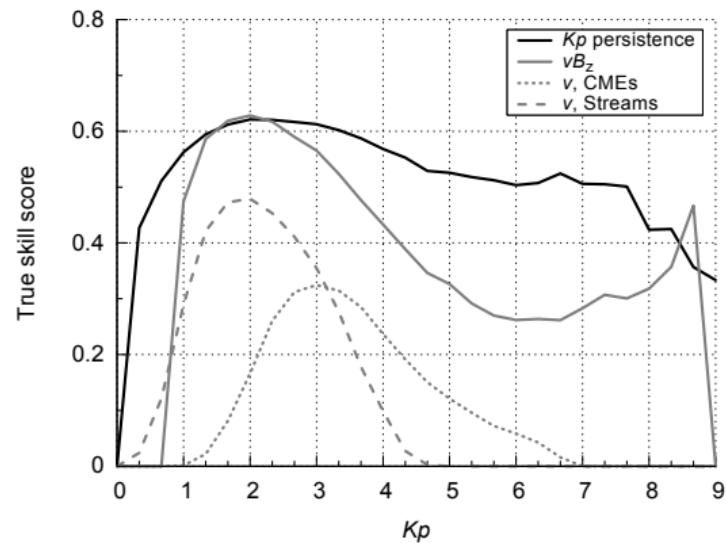
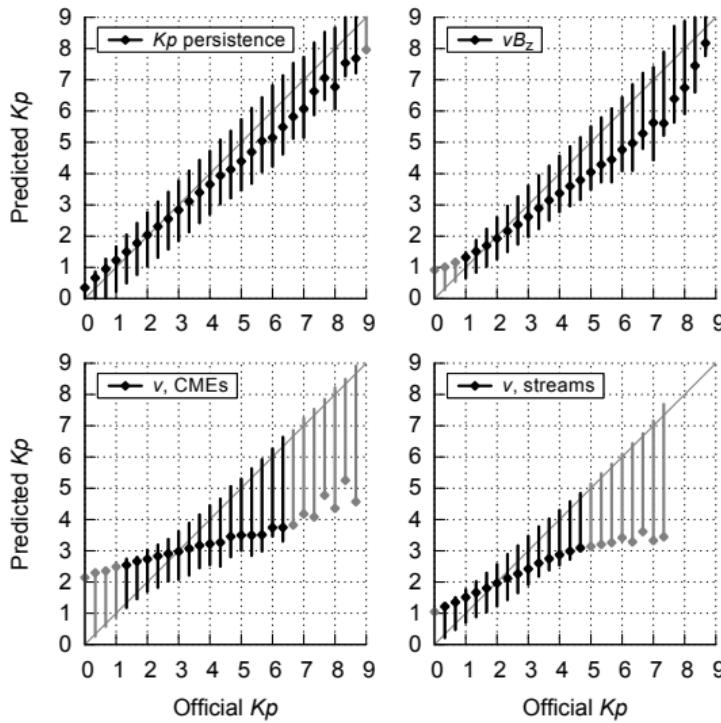


Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

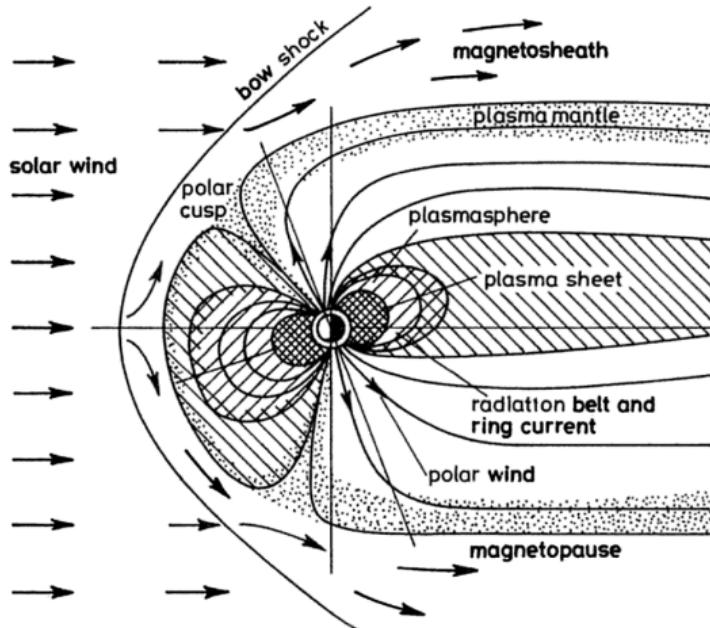
## $Kp$ long-term variations



# Prediction performance



# Magnetosphere

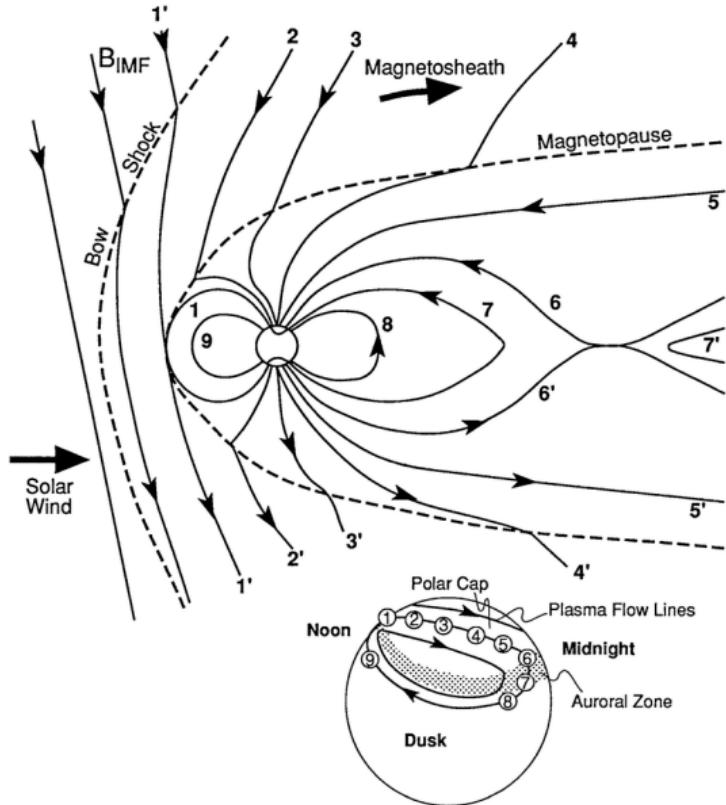


Credit: Davies (1990, Fig. 2.12)

Interaction mechanisms between solar wind and magnetosphere:

- Reconnection
- Turbulence
- Compression
- Induction

# Magnetosphere



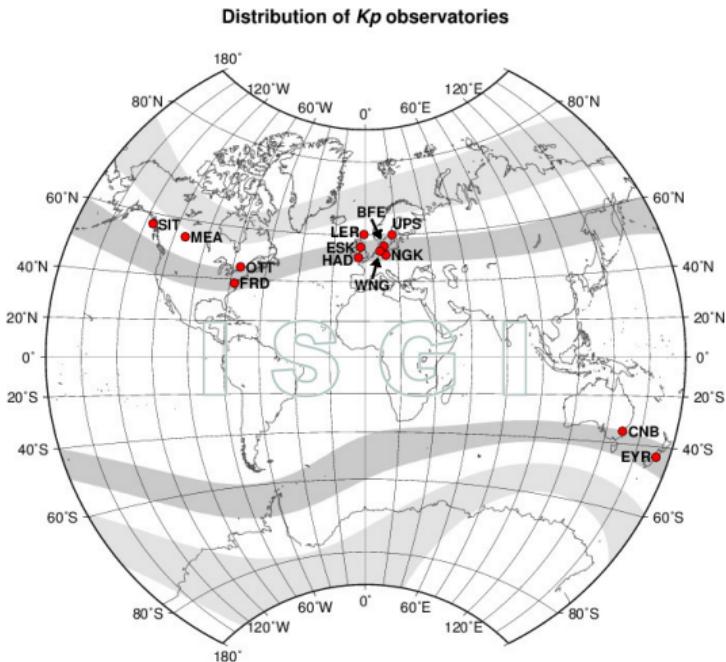
Credit: Hughes (1995, Fig. 9.11)

Factors that influence the reconnection flux rate:

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

# *Kp* index

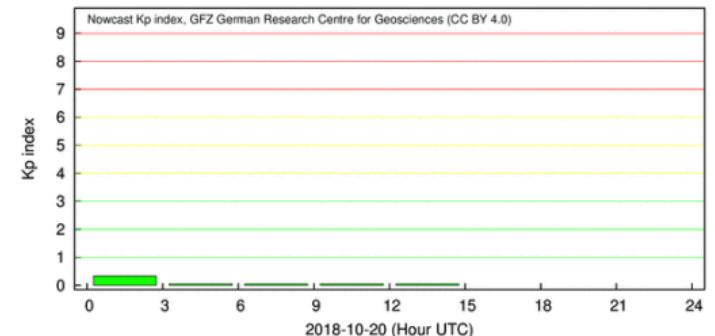
- Planetary geomagnetic disturbance indicator
- 3-hourly variation maxima
- 13 observatories at 50° geomagnetic latitudes
- Scale from 0 to 9



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

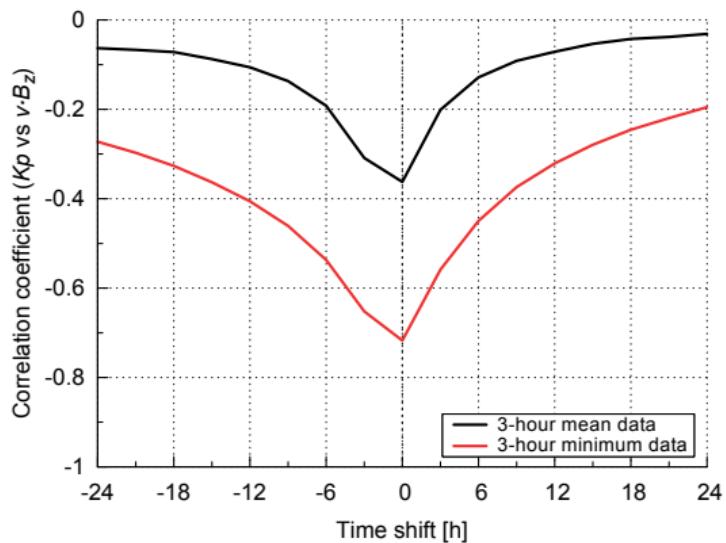
# *Kp* index

## Quicklook *Kp*

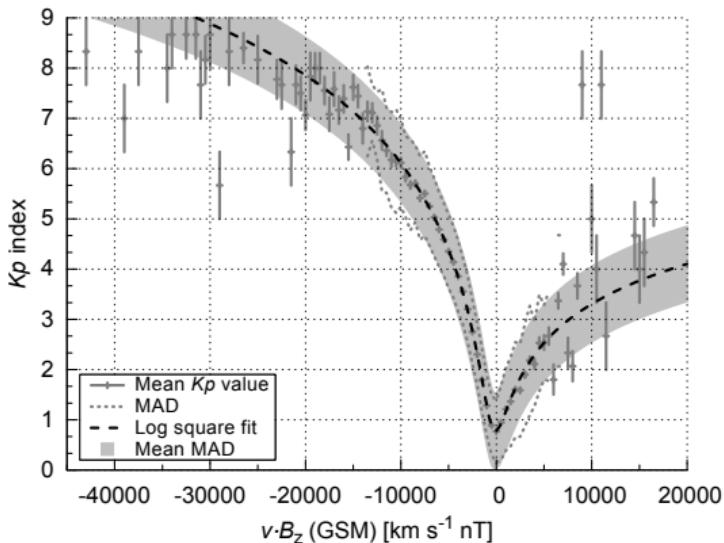
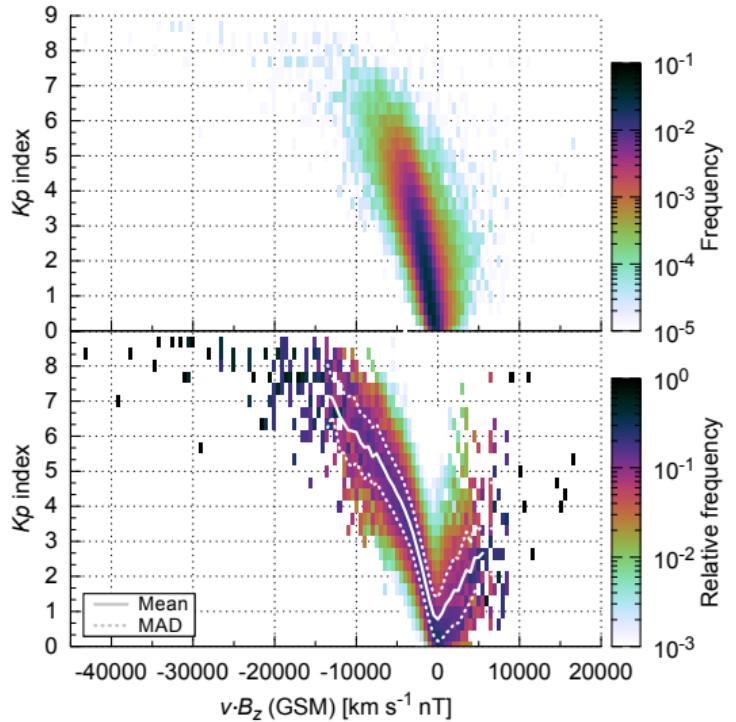


Credit: GFZ Potsdam, 2018

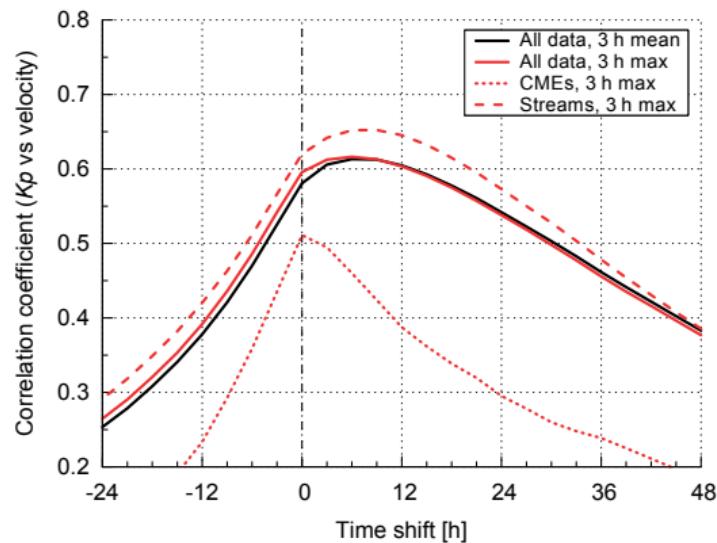
# Solar wind electric field



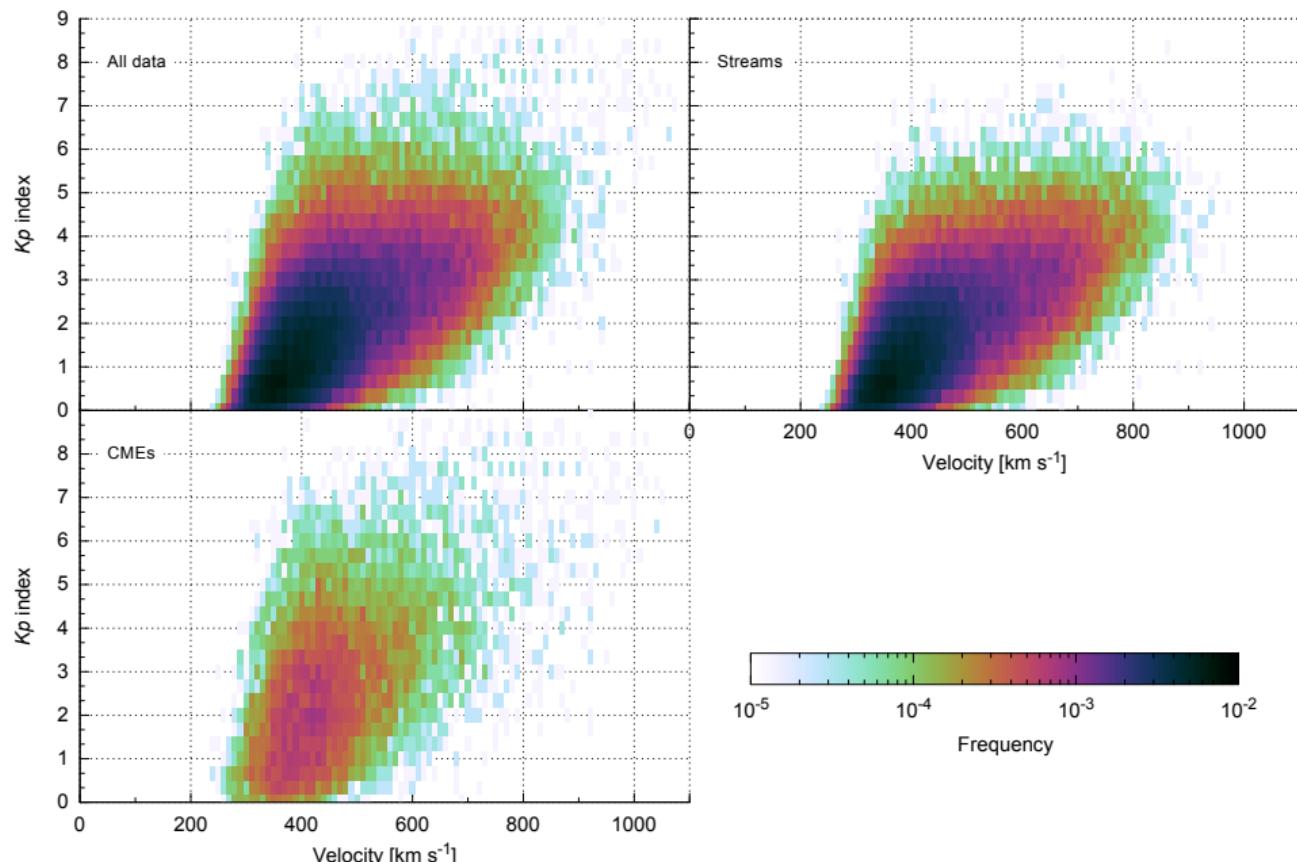
# Solar wind electric field

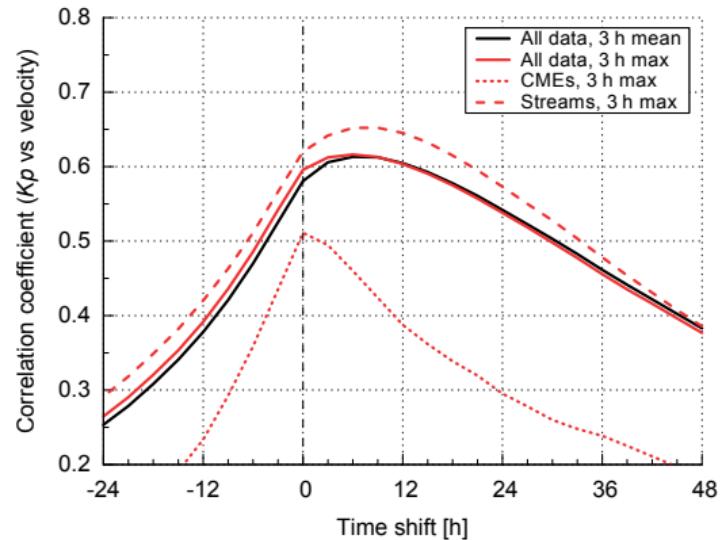


# Solar wind velocity

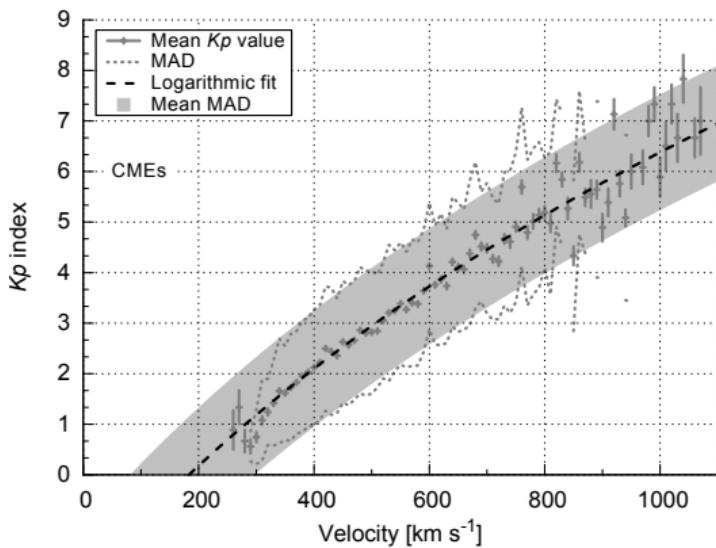
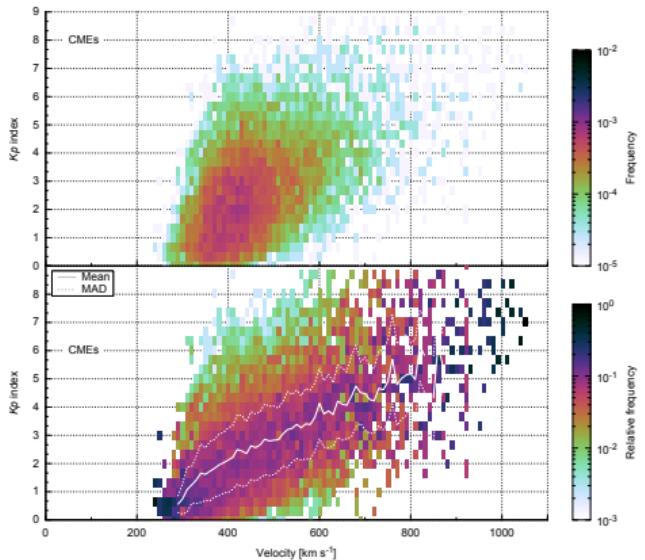


# Solar wind velocity

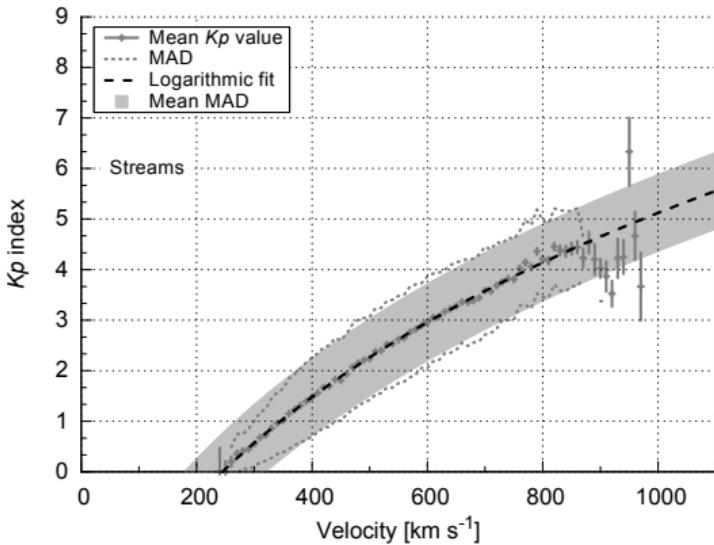
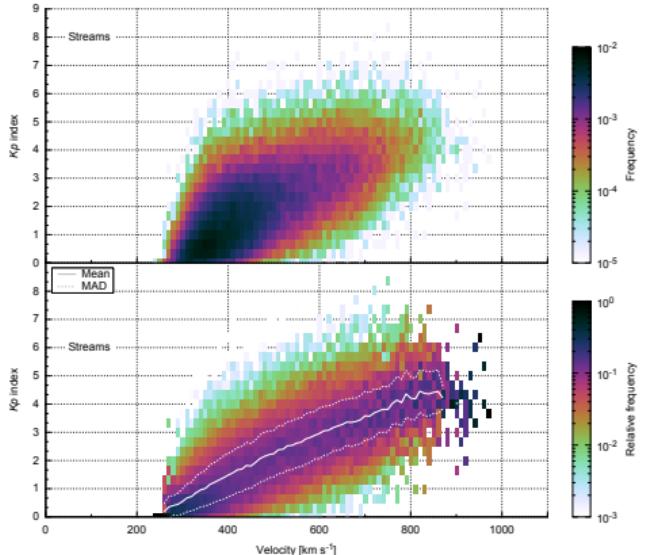


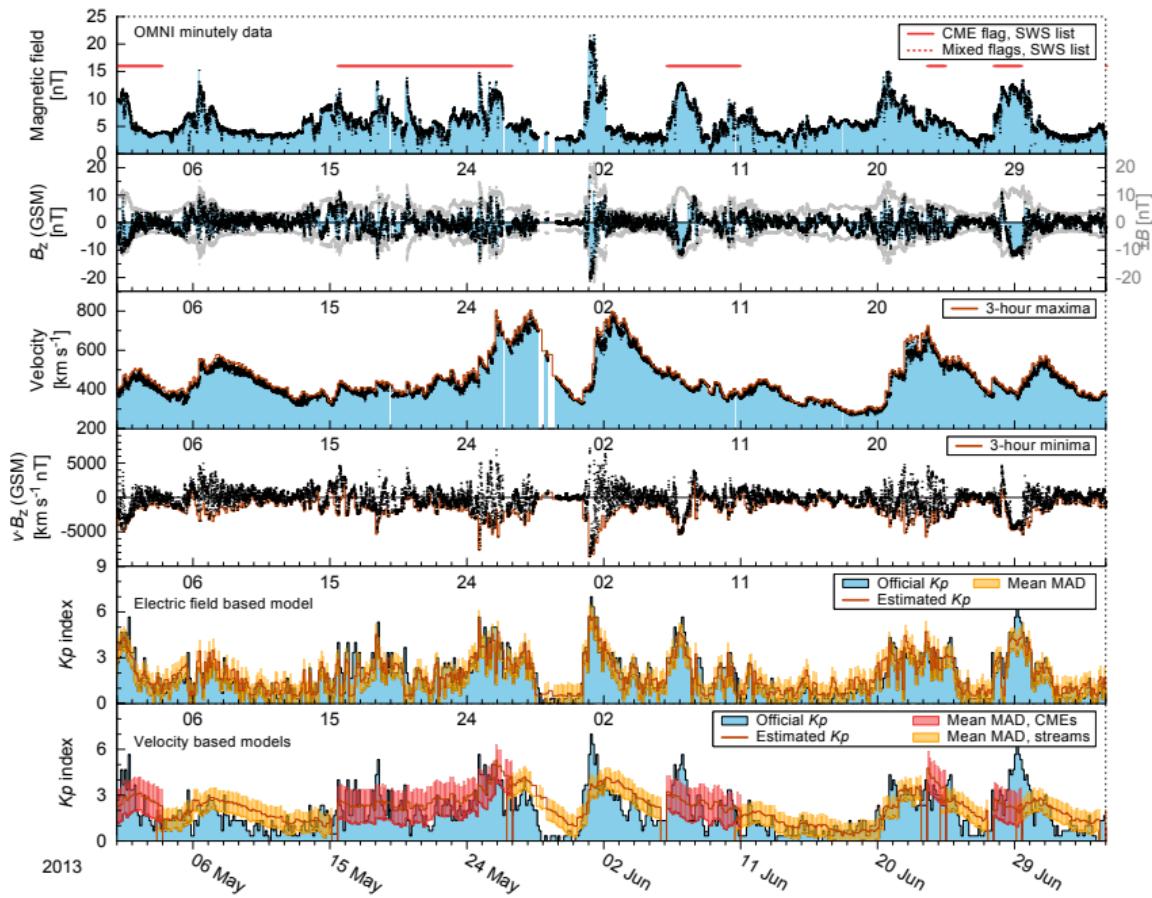


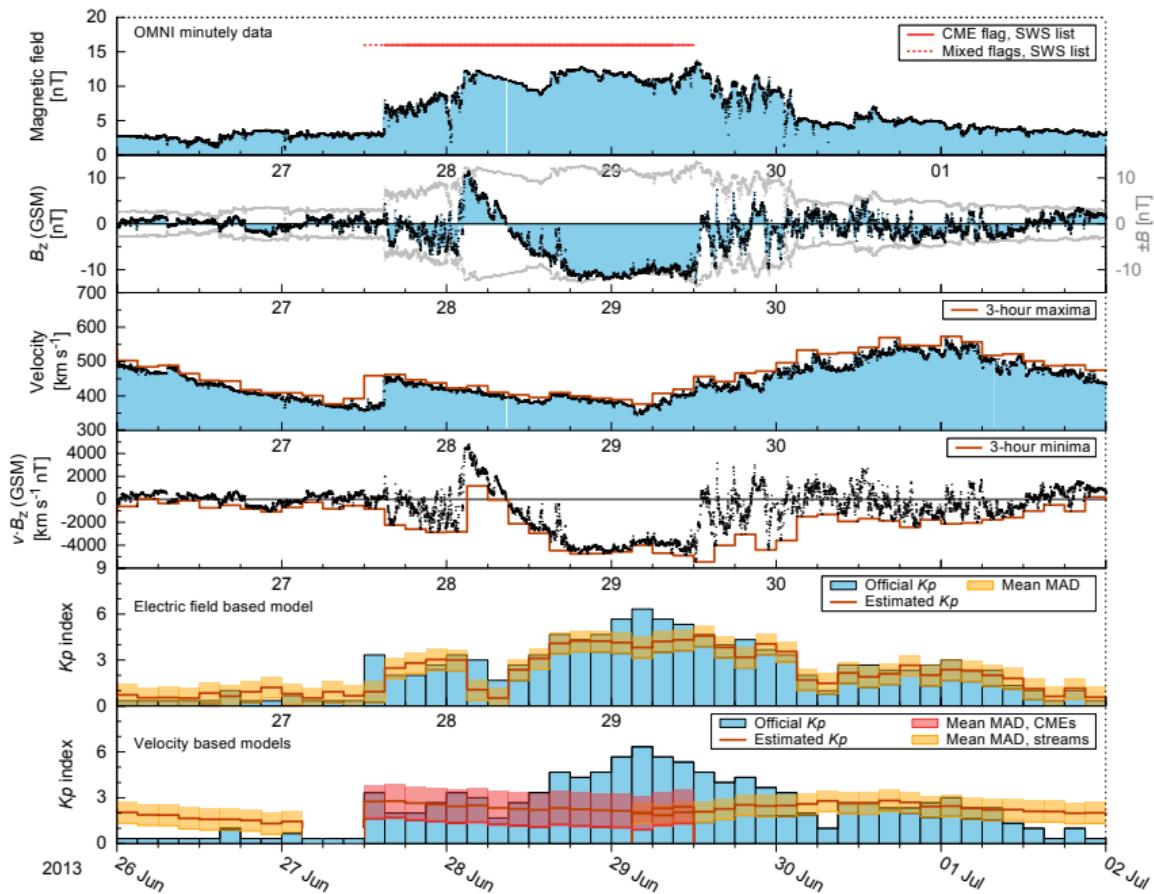
# CME velocity



# Stream velocity







## Results

Predictive  $K_p$  models based on relations with

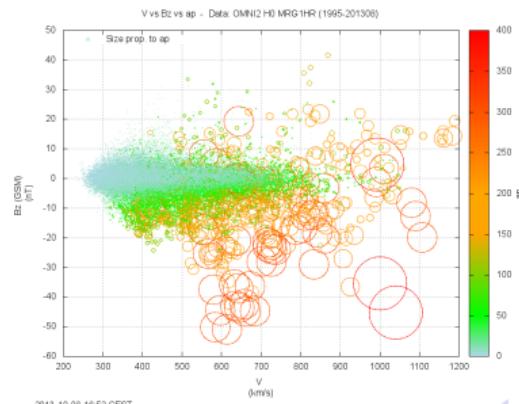
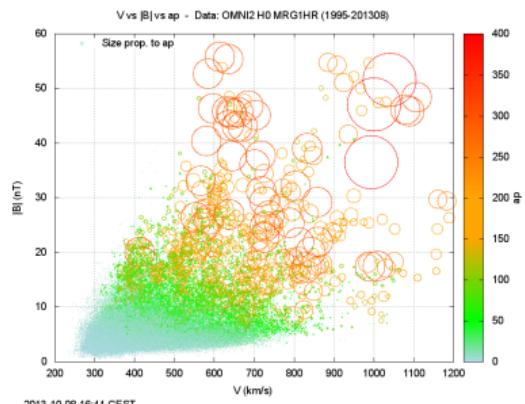
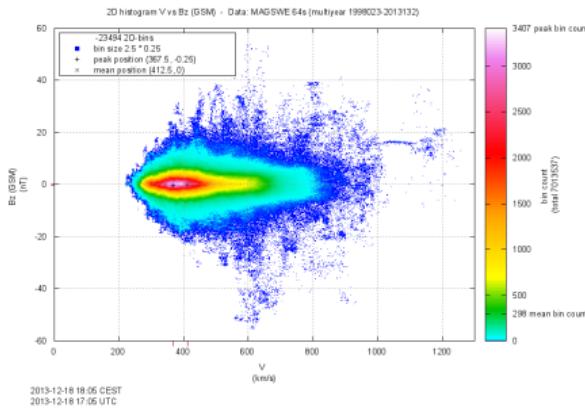
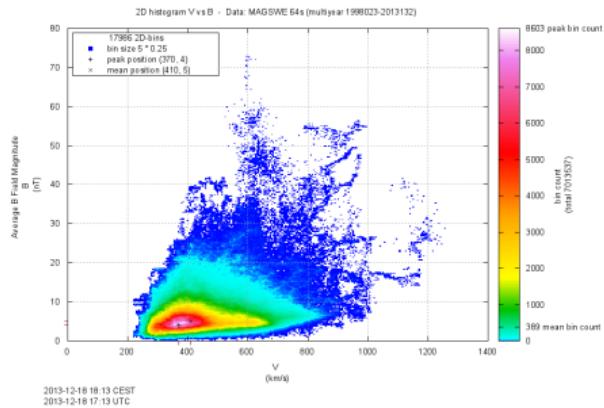
- Solar wind electric field proxy ( $vB_z$ )
- Velocity of CME-associated flows ( $v_{\text{CME}}$ )
- Velocity of solar wind streams ( $v_{\text{stream}}$ )

## Conclusions

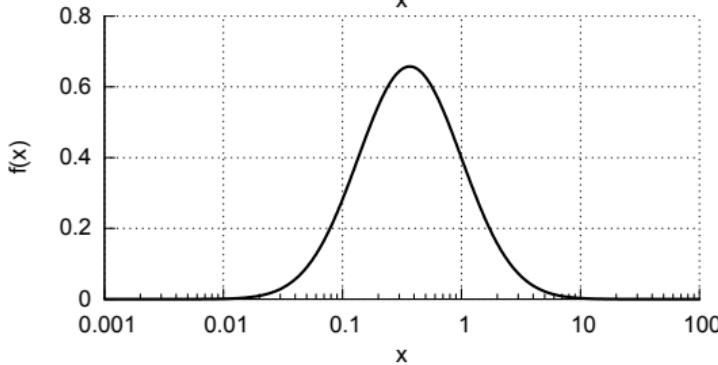
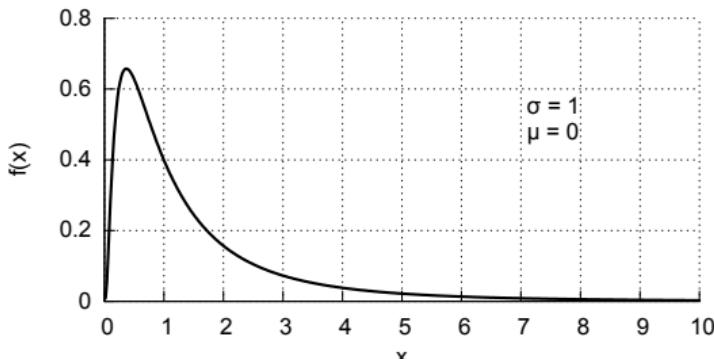
- The processing of 3-hour extrema of high time resolution data captures short-term geoeffective magnetic features that are neglected when averaging over 3-hour intervals
- The isolated treatment of CMEs and streams is beneficial to the prediction accuracy of  $K_p$
- The prediction models perform well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

» Prediction performance

# Solar wind



# 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:

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

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

Unsolved problems:

- Coronal heating mechanisms
- Solar wind acceleration processes
- Solar energetic particle sources

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

Primary goals are to investigate (Fox et al., 2015):

- the flow of energy that heats and accelerates the solar wind
- the structure and dynamics at the sources of the solar wind
- the mechanisms that accelerate solar energetic particles

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

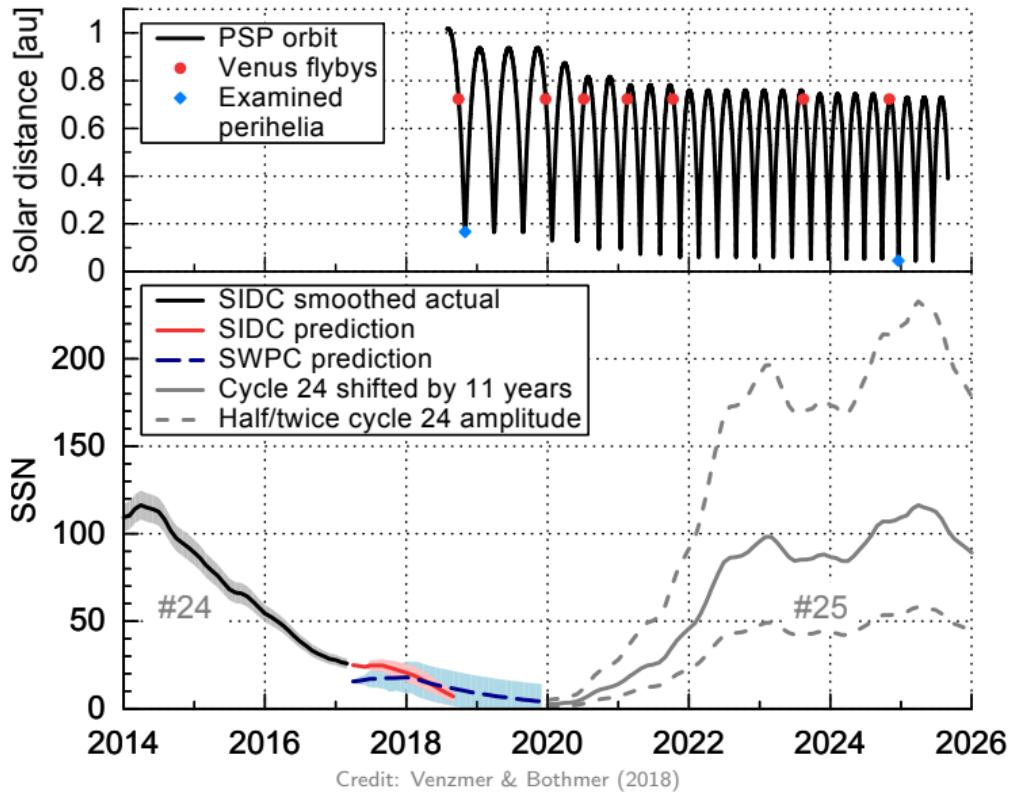
Primary goals are to investigate (Fox et al., 2015):

- the flow of energy that heats and accelerates the solar wind
- the structure and dynamics at the sources of the solar wind
- the mechanisms that accelerate solar energetic particles

## Scientific instruments

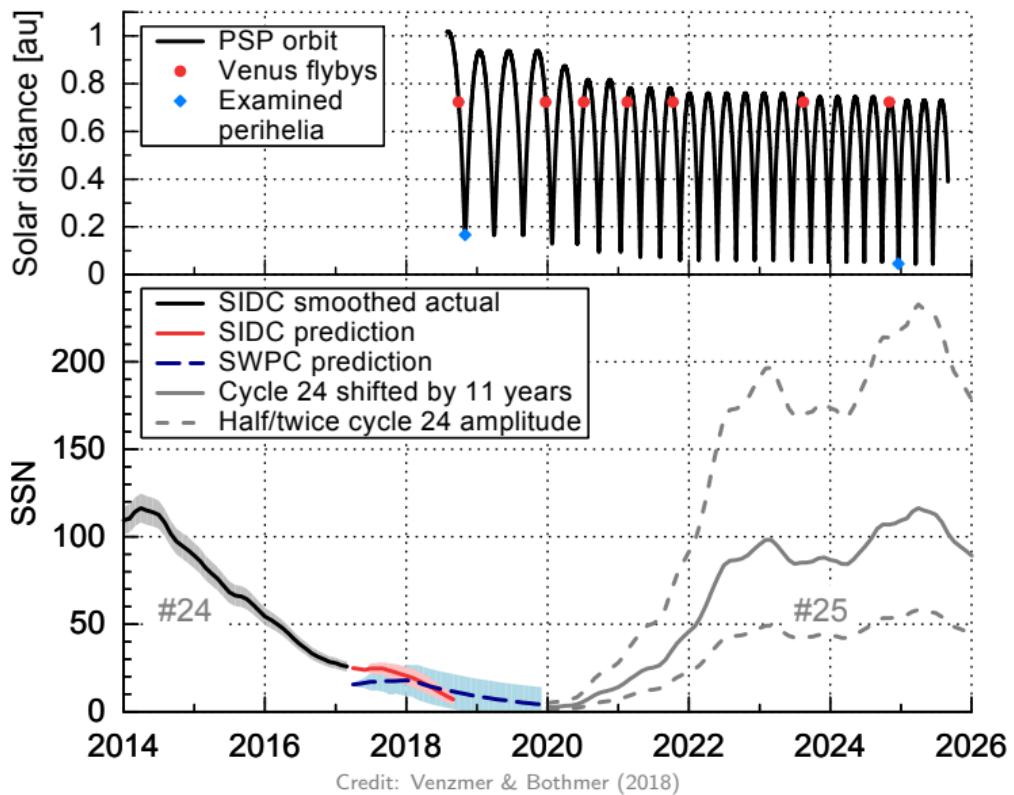
- FIELDS – Electromagnetic Fields Investigation
- IS $\odot$ IS – Integrated Science Investigation of the Sun
- SWEAP – Solar Wind Electrons Alphas and Protons Investigation
- WISPR – Wide-Field Imager for Solar Probe

# PSP distance and solar activity



Credit: Venzmer & Bothmer (2018)

# PSP distance and solar activity



Perihelion #1  
2018: solar minimum

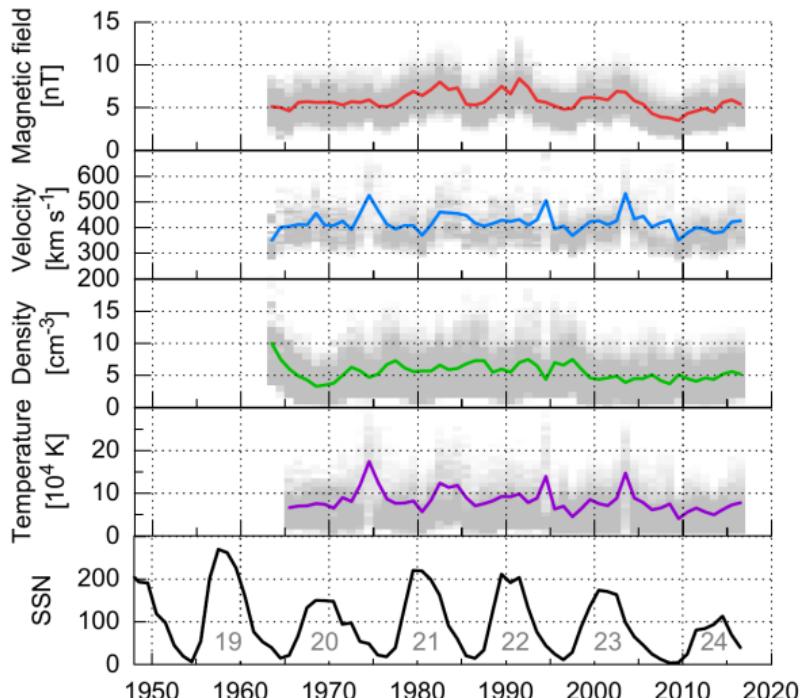
Perihelion #22  
2024: solar maximum

⇒ Predictive models have  
to be dependent on

- solar distance
- solar activity (SSN)

# Solar activity dependence – OMNI data

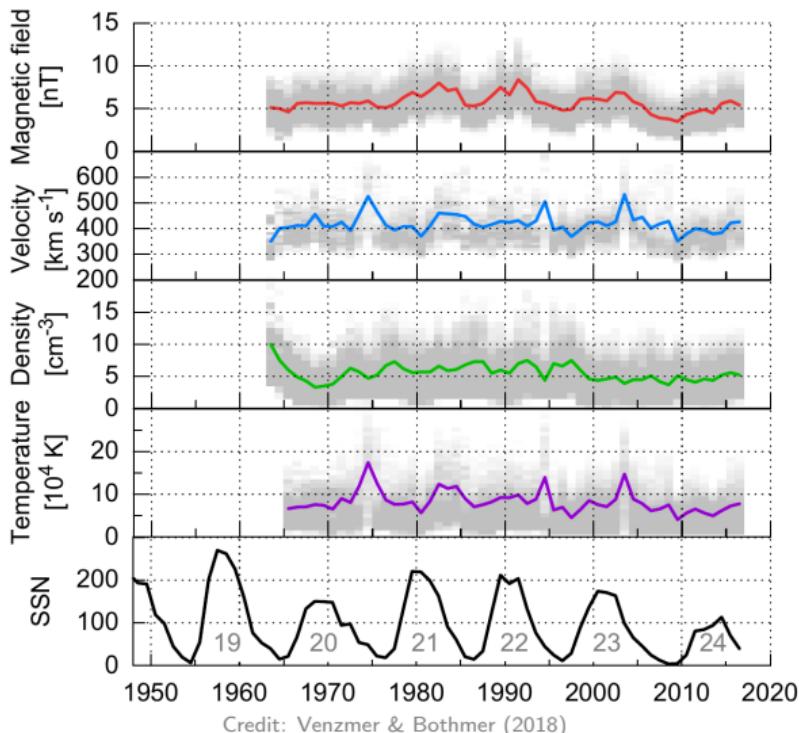
Yearly median values:



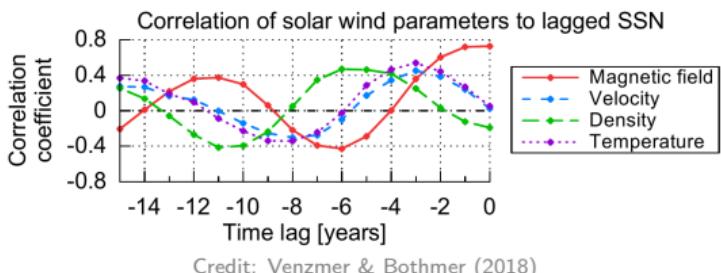
Credit: Venzmer & Bothmer (2018)

# Solar activity dependence – OMNI data

Yearly median values:

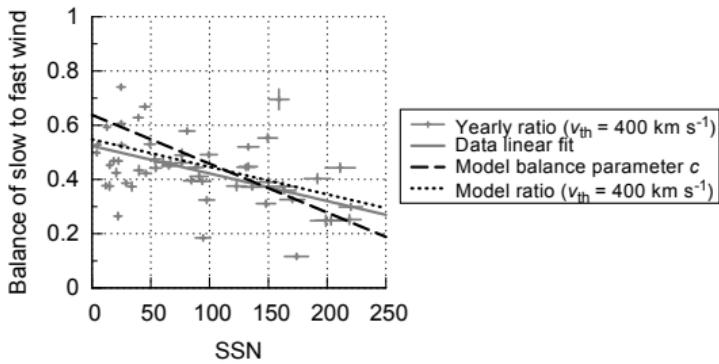
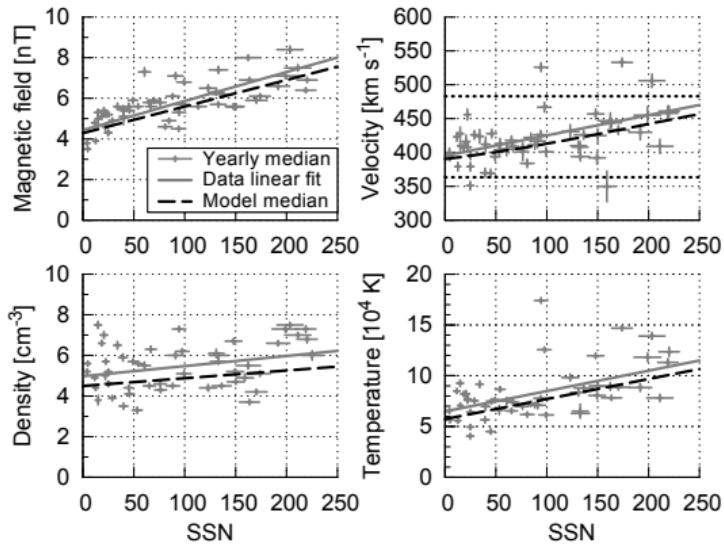


Find time lag with highest correlation coefficient:

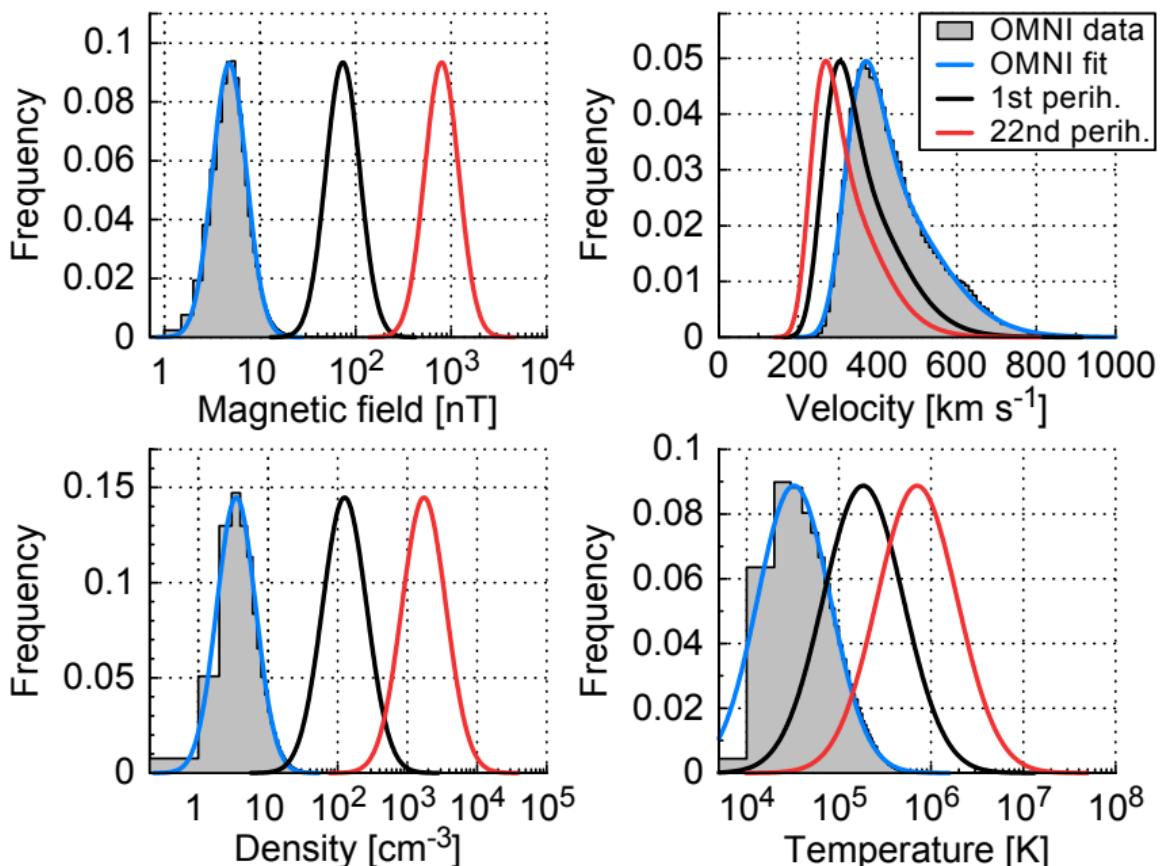


Credit: Venzmer & Bothmer (2018)

# Solar activity



# PSP perihelia prediction



# Solar wind

