

# 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  
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Thursday, 1 November 2018, 14:00  
Seminarraum Astrophysik (SR 17, F 05.104)

## Two topics

The solar wind's geomagnetic impact and its Sun–Earth evolution  
Predictive models for space weather and for the Parker Solar Probe orbit

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### Study 1

The solar wind's geomagnetic impact – Predictive models for space weather

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## Study 1

The solar wind's geomagnetic impact – Predictive models for space weather

## Study 2

The solar wind's Sun–Earth evolution – Predictive models for the Parker Solar Probe orbit

# Contents

- Study 1 – A brief summary
- Study 2 – More detailed
  - Intro
  - Parker Solar Probe
  - Solar wind model
  - Prediction for PSP

# Geomagnetic impact of the solar wind

Solar wind – solar system bodies

CMEs – geomagnetic storms – effects

importance of prediction of onset/magnitude

The study addresses; deriving predictive models



# Solar wind

- E. Parker's theoretical model
- confirmation by in-situ measurements
- monitored continuously near Earth since

measured in-situ throughout the heliosphere:  

- Voyager – heliopause
- Ulysses – high heliolatitudes
- Helios – Mercury

# Solar wind



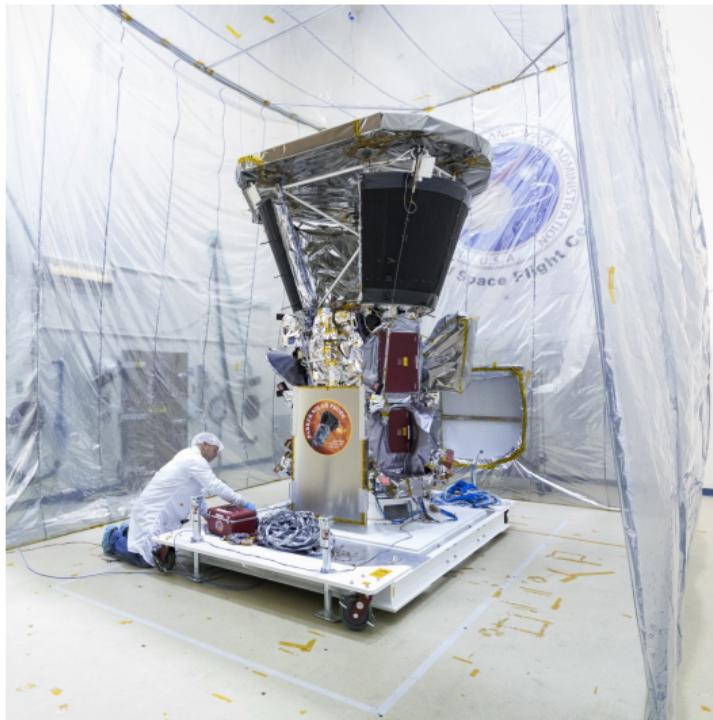
Credit: Miloslav Druckmüller, Peter Aniol, Shaddia Habbal, 2017

The near-Sun region is of special scientific interest:

- coronal heating
- solar wind acceleration

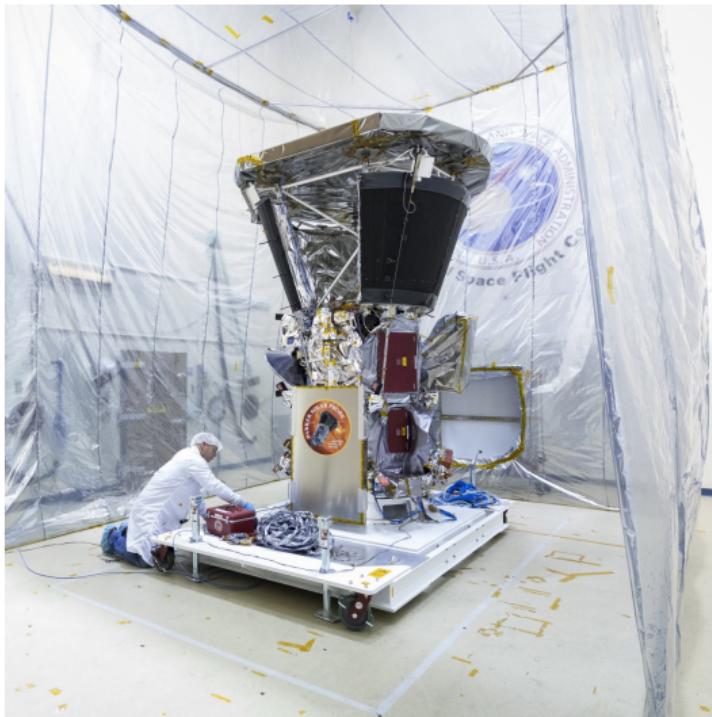
list potential mechanisms...

# Parker Solar Probe

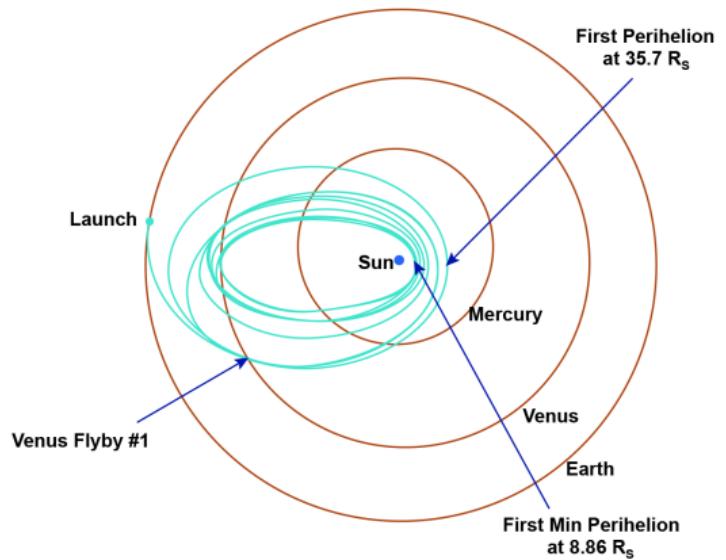


Credit: NASA/Johns Hopkins APL/Ed Whitman, 2017

# Parker Solar Probe



Credit: NASA/Johns Hopkins APL/Ed Whitman, 2017



Credit: NASA/Johns Hopkins APL, 2018

# Parker Solar Probe



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

# Parker Solar Probe



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

- 12 August 2018: launched
- 3 October: Venus flyby
- 29 October: closest s/c ever ( $63.5 R_{\odot}$ )
- 6 November: first perihelion ( $36.7 R_{\odot}$ )
- 24 December 2024: first closest perihelion ( $9.86 R_{\odot}$ )

# Parker Solar Probe

PSP mission 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

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WISPR coronagraph (Wide-Field Imager for Solar Probe)

This study is based on work performed for the CGAUSS (Coronagraphic German and US SolarProbePlus Survey) project

# Solar wind model

## Aim

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

# Solar wind model

## Model concept

Four solar wind key parameters

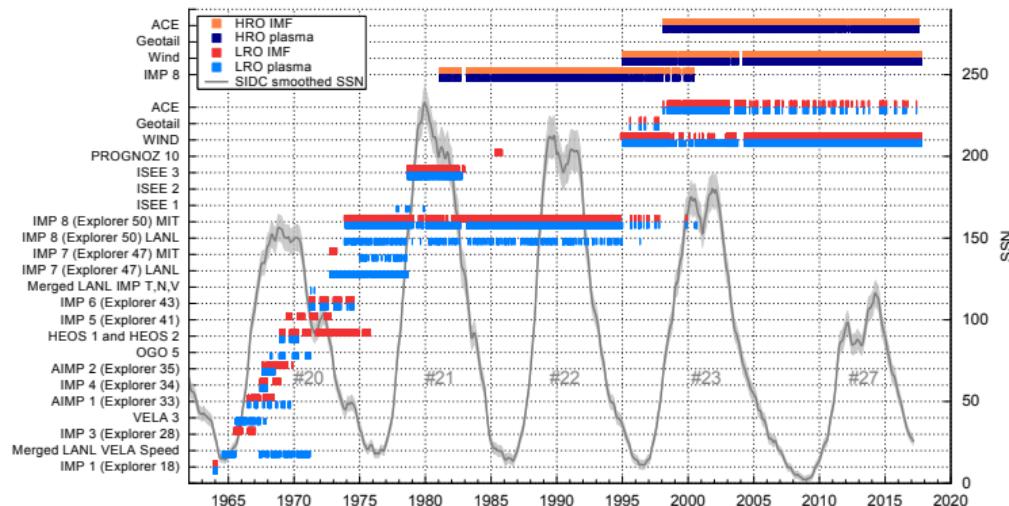
- Magnetic field strength
- Velocity
- Density
- Temperature

values shifted according to solar activity and solar distance

unique: frequency distributions

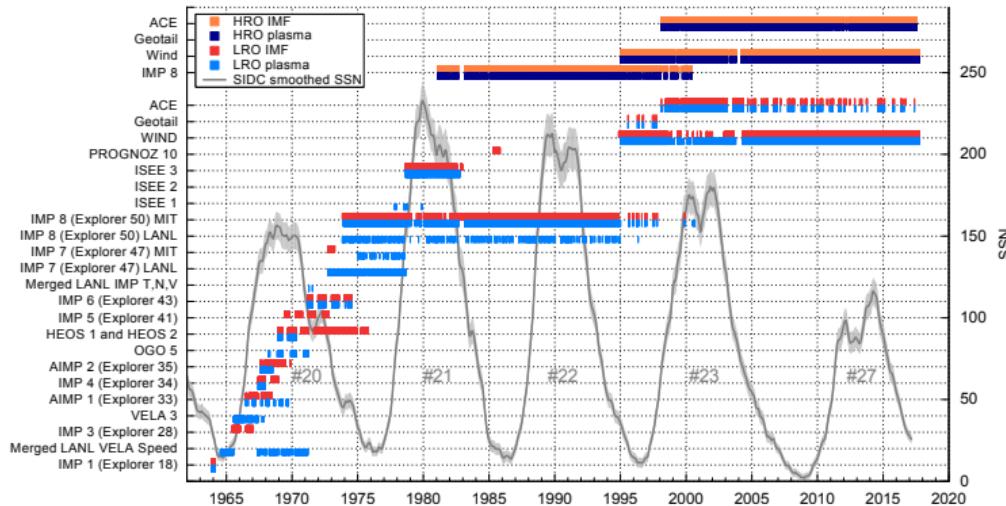
# OMNI data set

OMNI data set (King & Papitashvili, 2005)  
- intercalibrated multi-spacecraft data



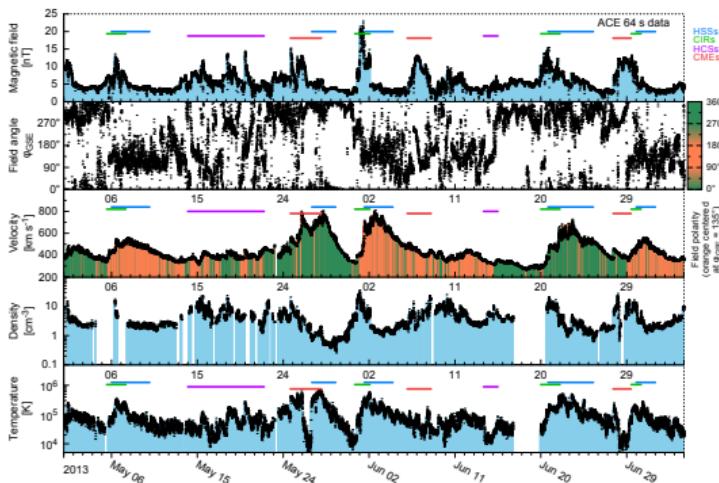
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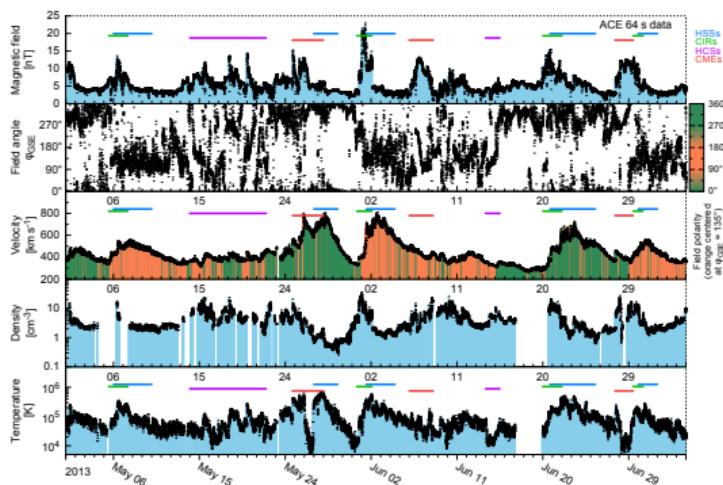
- time-shifted to the bow shock of the magnetosphere
- 1963–2016

# OMNI data set



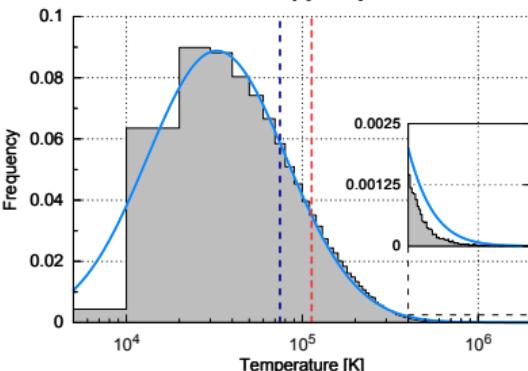
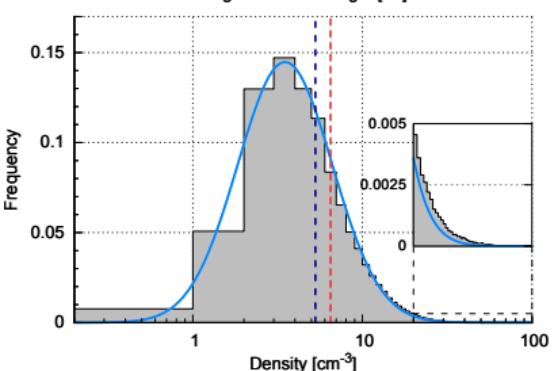
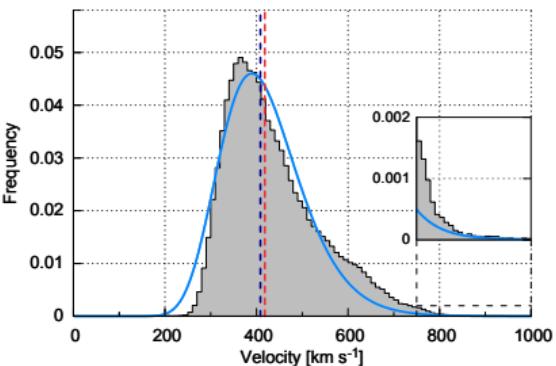
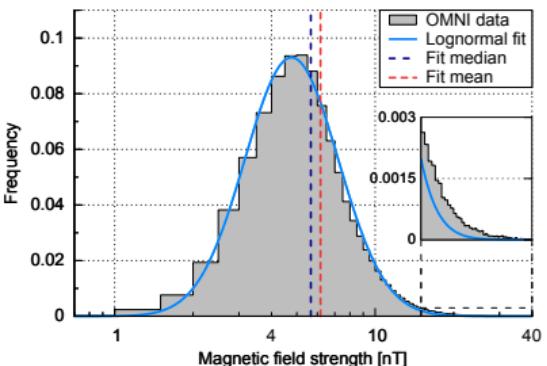
example data plots...

# OMNI data set

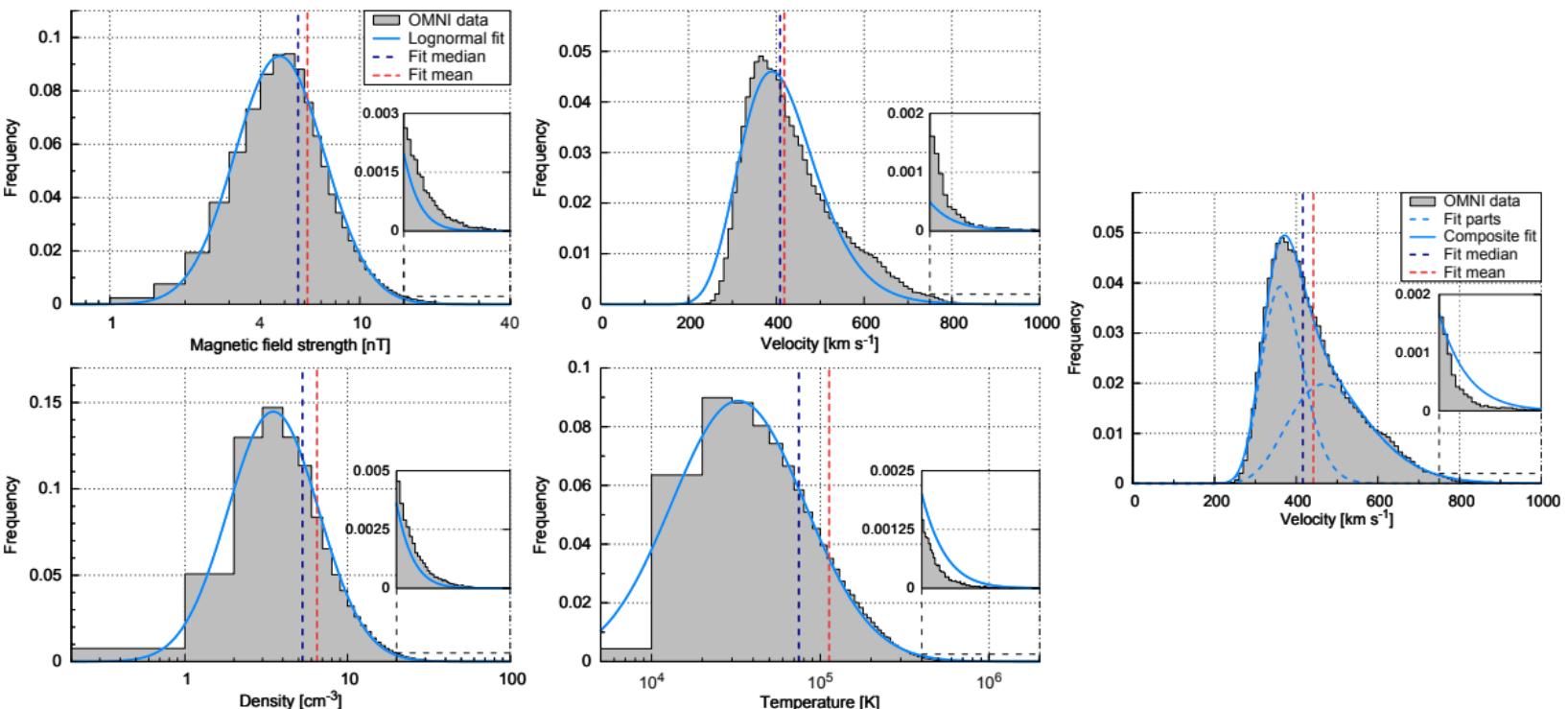


example data plots...

# Frequency distributions

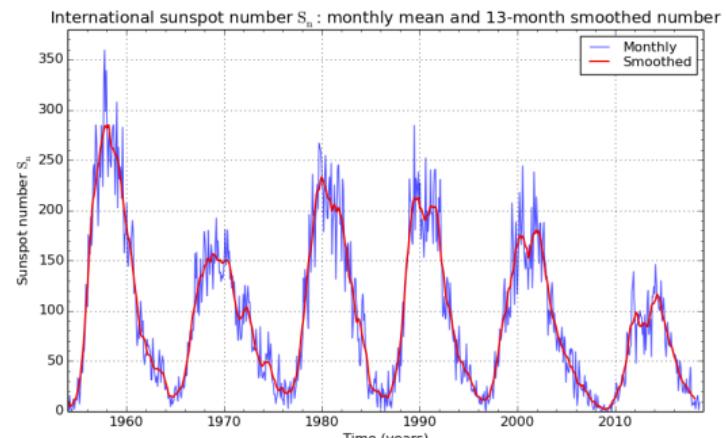


# Frequency distributions



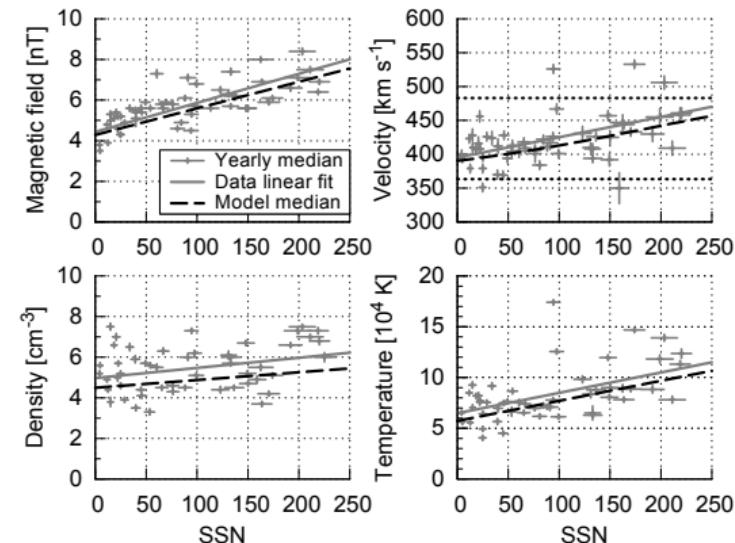
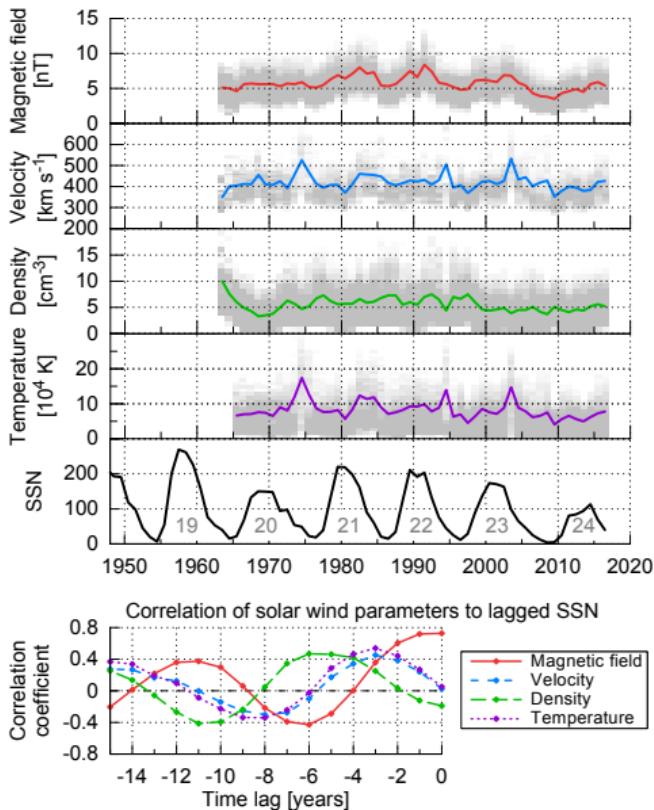
# Solar activity

sunspot images...

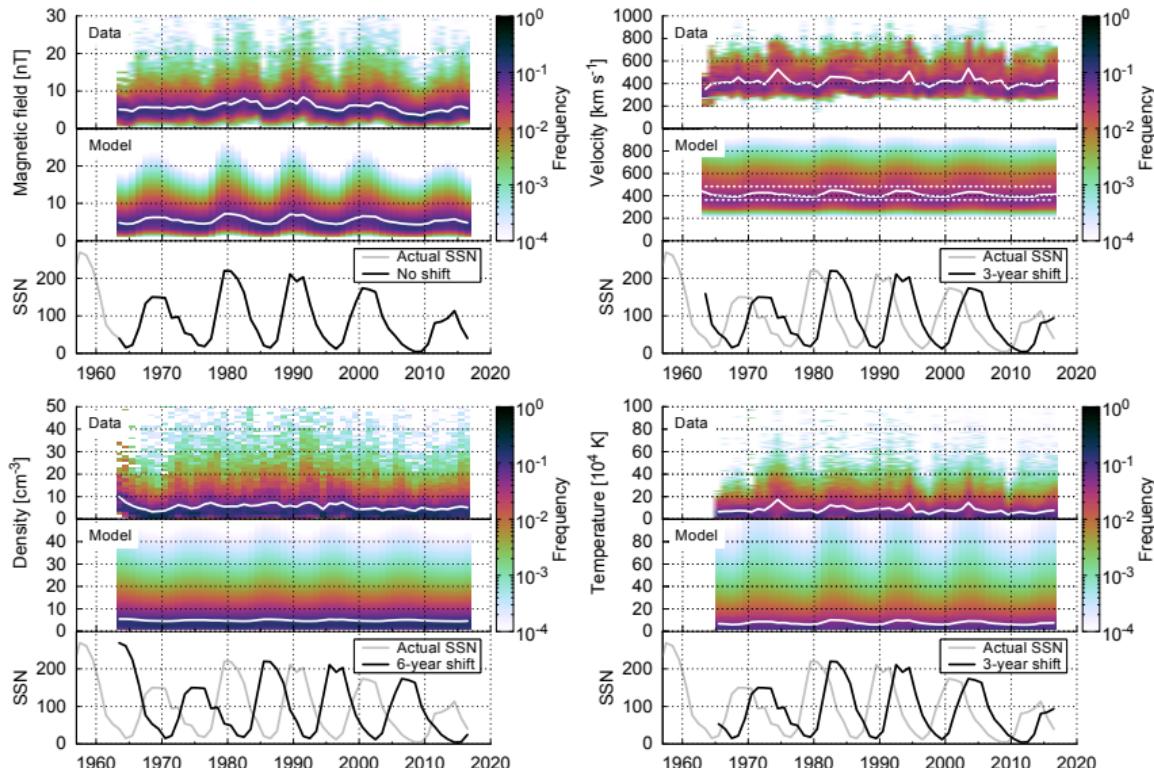


» Magnetic butterfly diagram

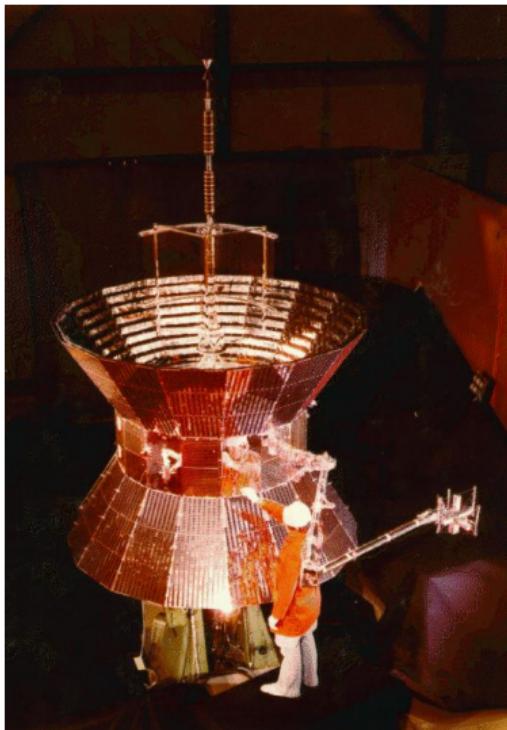
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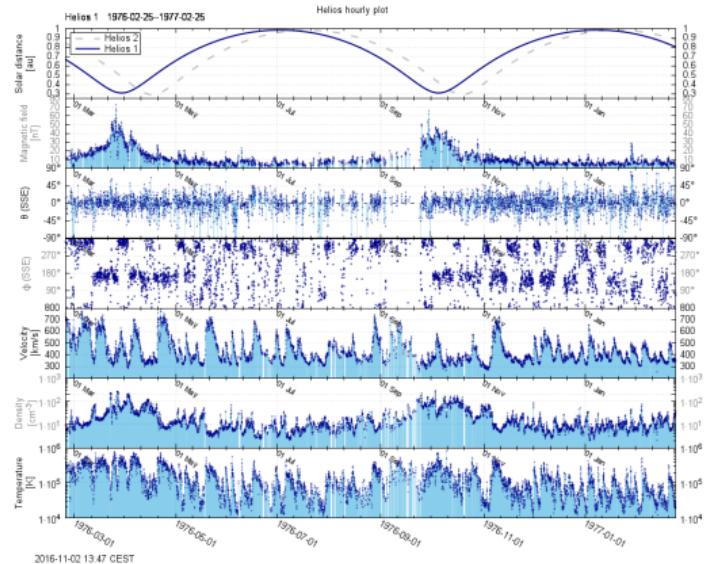


# Helios data

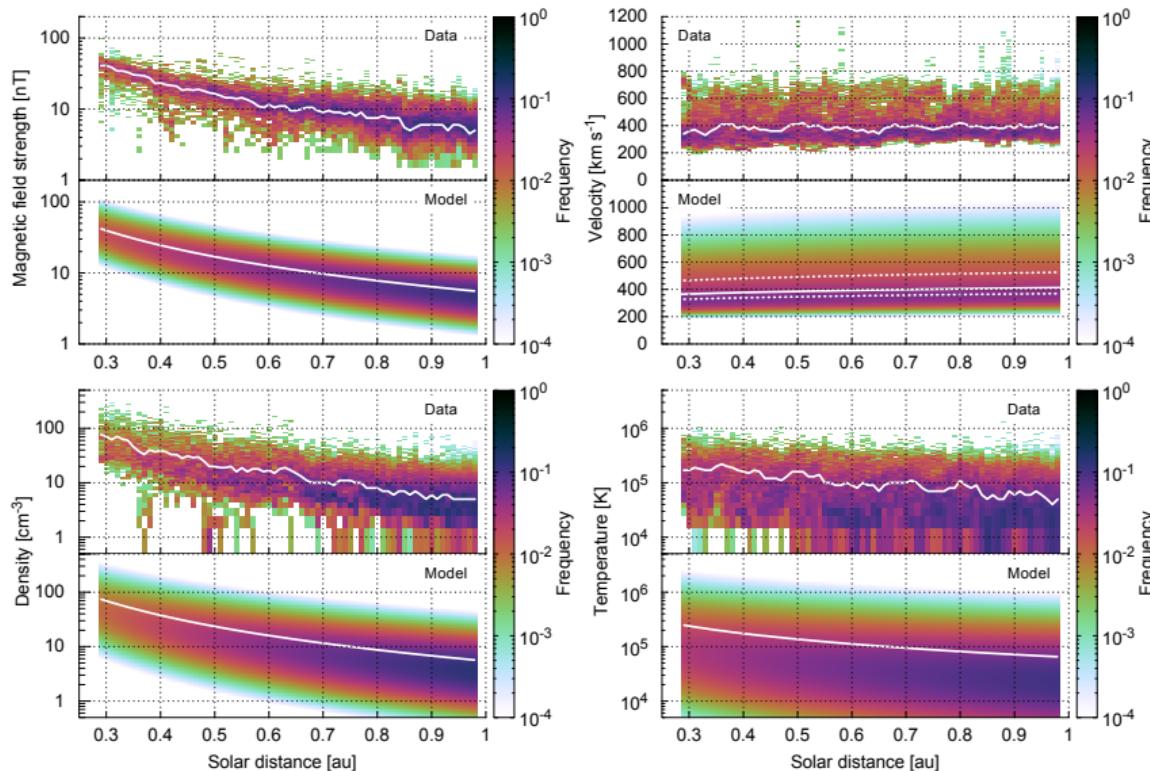


Credit: NASA

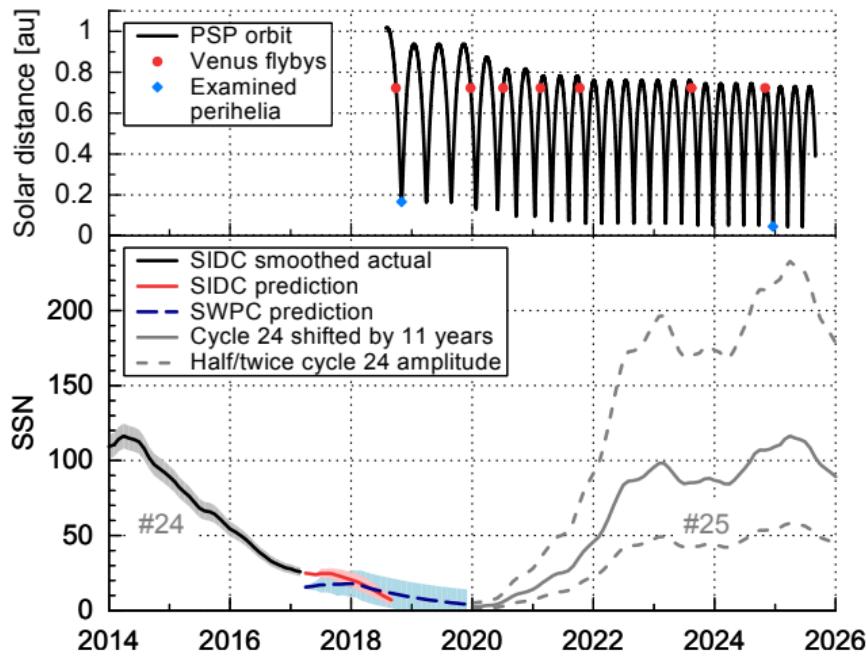
Helios 1 and Helios 2  
hourly data set (Rosenbauer et al., 1977)  
0.29–0.98 au  
1974–1981



# Solar distance

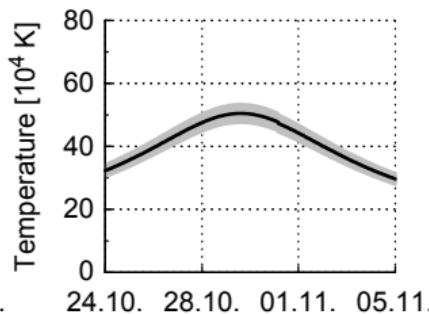
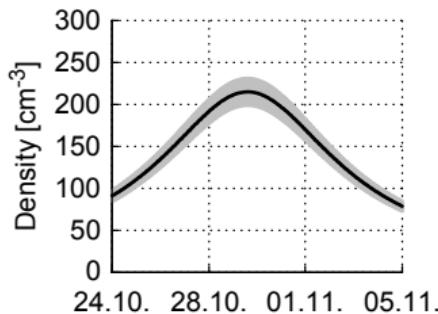
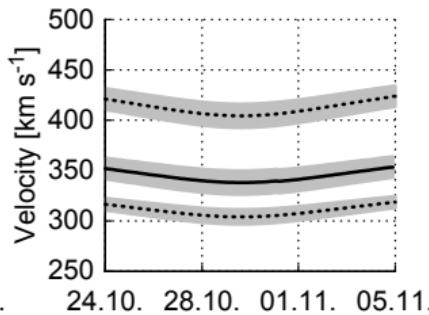
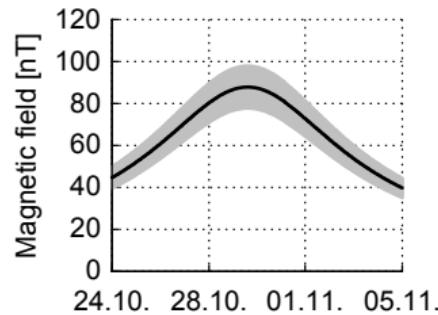


# PSP distance and SSN prediction



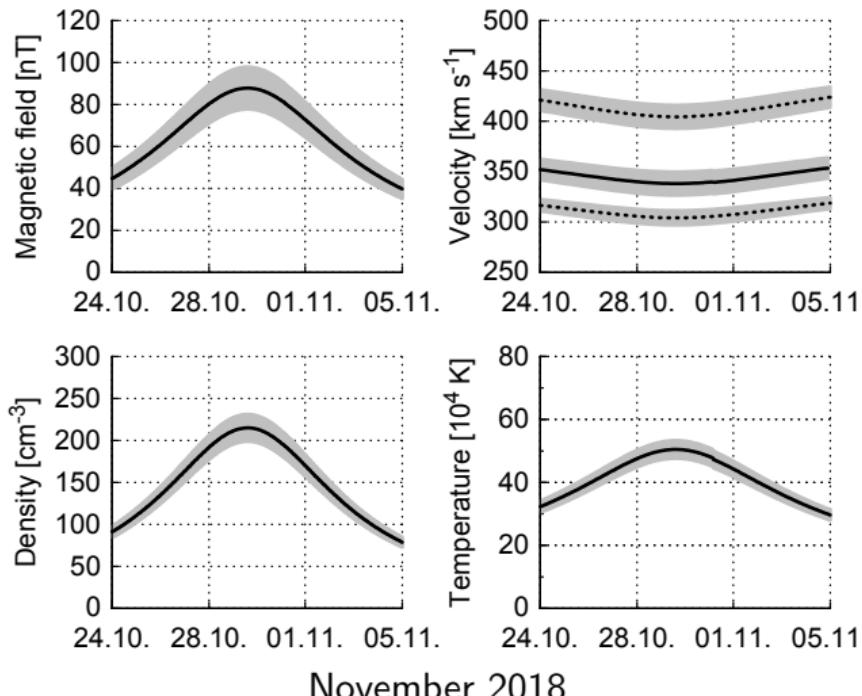
# PSP orbit prediction

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



November 2018

# PSP orbit prediction

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

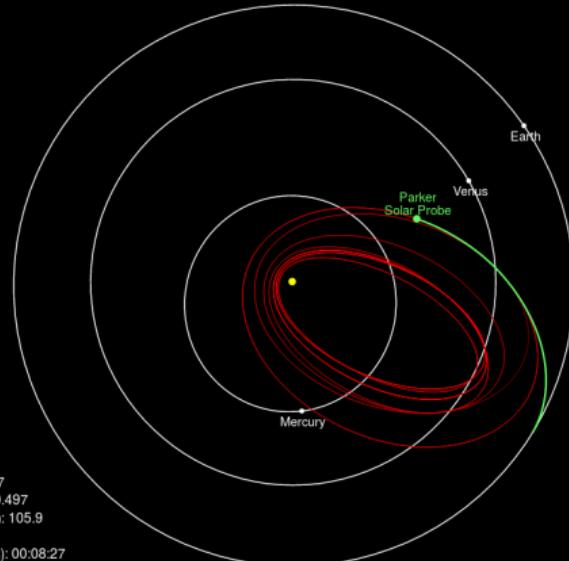
November 2018

## Predicted values

$$\begin{aligned}B &= 94 \text{ nT} \\v &= 340 \text{ km s}^{-1} \\n &= 214 \text{ cm}^{-3} \\T &= 5.03 \times 10^5 \text{ K}\end{aligned}$$

# PSP's current position

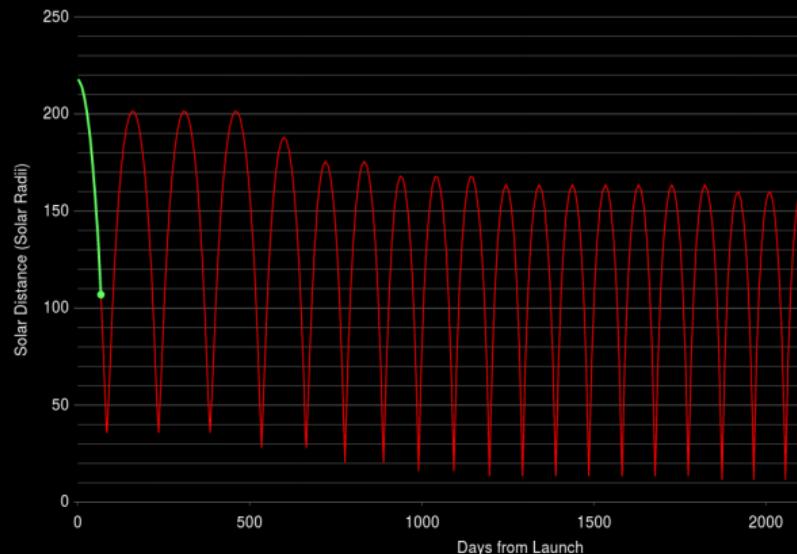
Parker Solar Probe Mission Trajectory and Current Position



Heliocentric Velocity (km/s): 44.27  
Distance from Sun Center (AU): 0.497  
Distance from Sun's Surface ( $R_S$ ): 105.9  
Distance from Earth (AU): 0.508  
Round-Trip Light Time (hh:mm:ss): 00:08:27  
19 Oct 2018 14:00:00 UTC

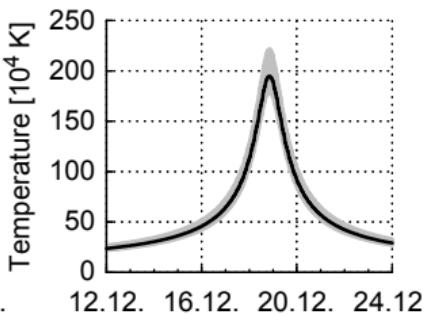
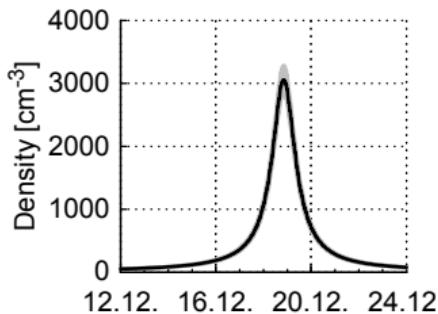
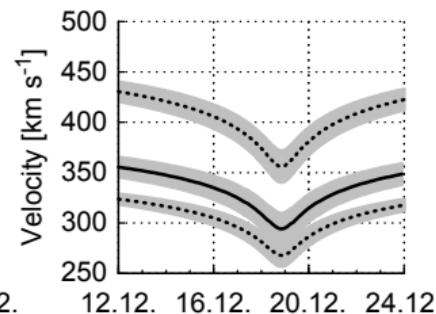
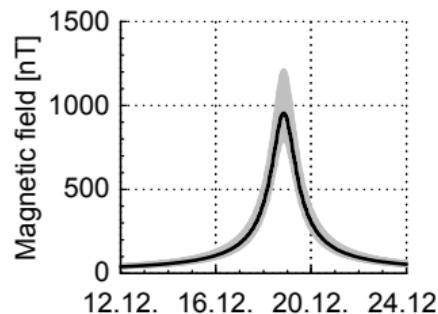
Credit: NASA

Parker Solar Probe Distance from Sun



# PSP orbit prediction

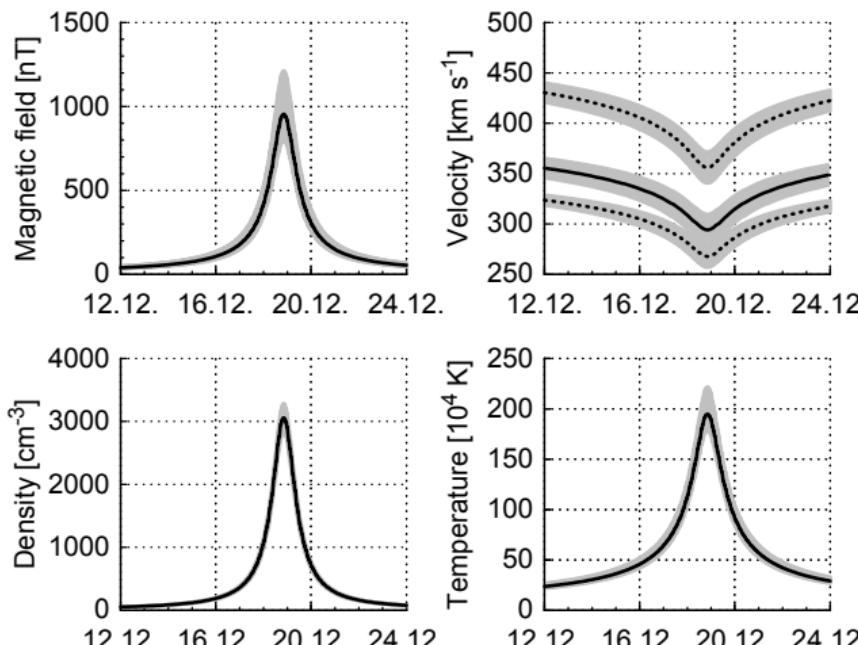
Perihelion #22 at  $9.86 R_{\odot}$  (first closest)



December 2024

# PSP orbit prediction

Perihelion #22 at  $9.86 R_{\odot}$  (first closest)



## Predicted values

$$\begin{aligned}B &= 1241 \text{ nT} \\v &= 290 \text{ km s}^{-1} \\n &= 2951 \text{ cm}^{-3} \\T &= 1.93 \times 10^6 \text{ K}\end{aligned}$$

### Predicted values

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

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

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

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Remote observations show the limits of the model:

- Studies reveal slow wind velocities of  $200 \text{ km s}^{-1}$  (Sheeley et al., 1997; Wang et al., 2000)
- Near-Sun coronal temperatures yield 2–3 MK (Billings, 1959; Liebenberg et al., 1975)

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⇒ Solar wind is still being heated and accelerated up to  $20 R_\odot$

# Outlook

- Investigate near-Sun properties of inner solar wind structures
- Modifications to model
- Refine model with additional solar wind data:
  - from Mercury probes
  - from Solar Orbiter
  - from Parker Solar Probe

# Summary

- Predictive models that relate geomagnetic disturbances with specific solar wind parameters:
  - solar wind electric field
  - CME velocity
  - stream velocity
- Empirical solar wind model for the inner heliosphere that considers solar activity and solar distance
  - Extrapolation of the model to the near-Sun environment for the PSP orbit
  - Solar wind prediction for PSP's first and first closest perihelia

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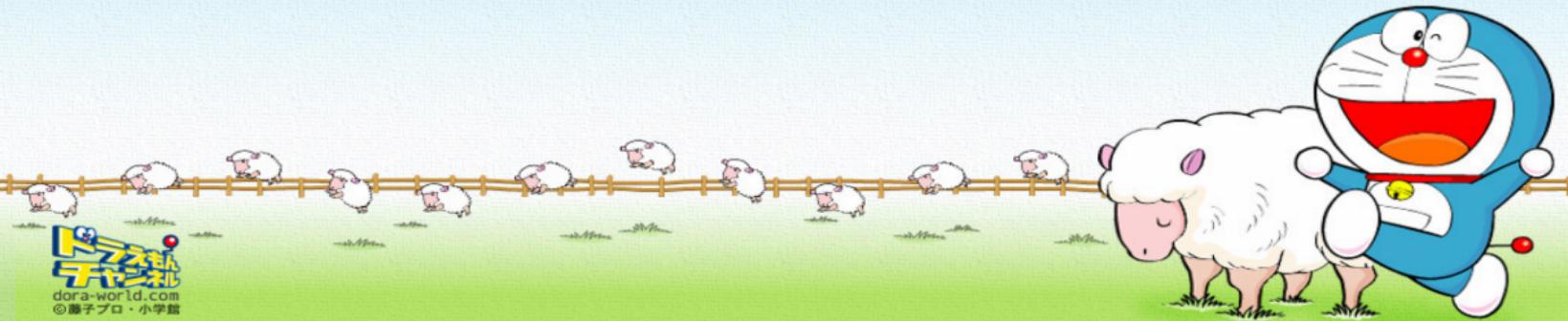
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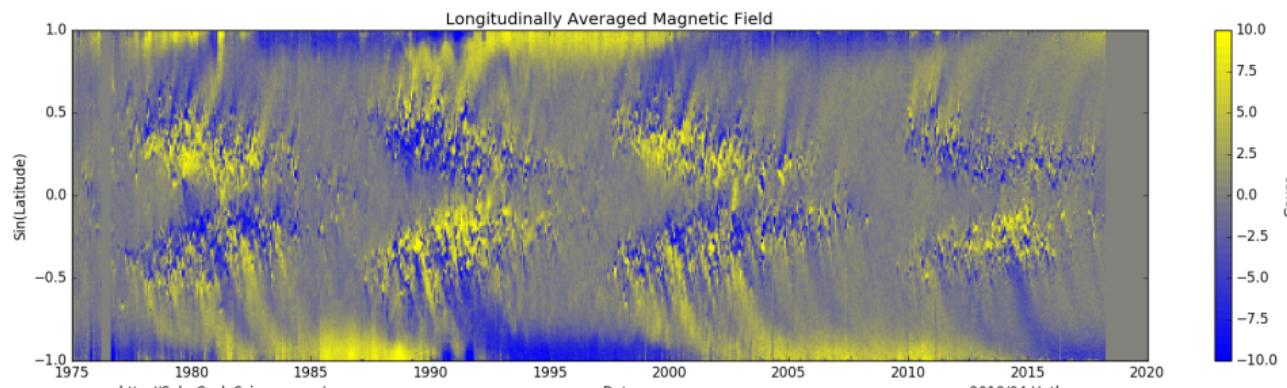


Thank you!



# Solar activity

## Magnetic butterfly diagram



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

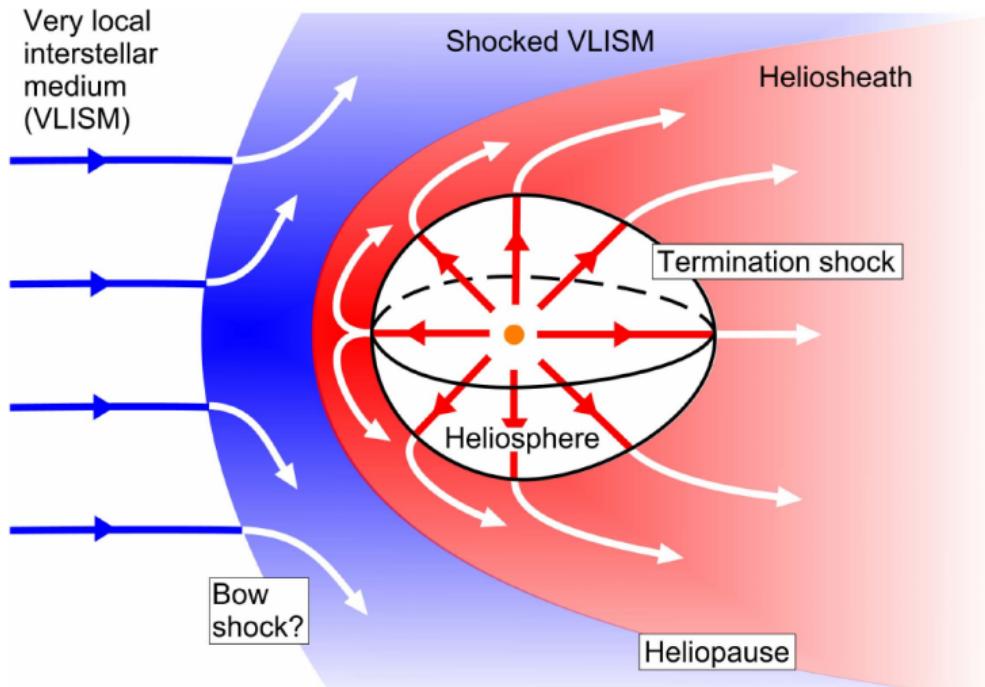
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Geomagnetic impact of the solar wind  
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Solar wind model for the inner heliosphere  
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Solar wind

## Solar wind



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

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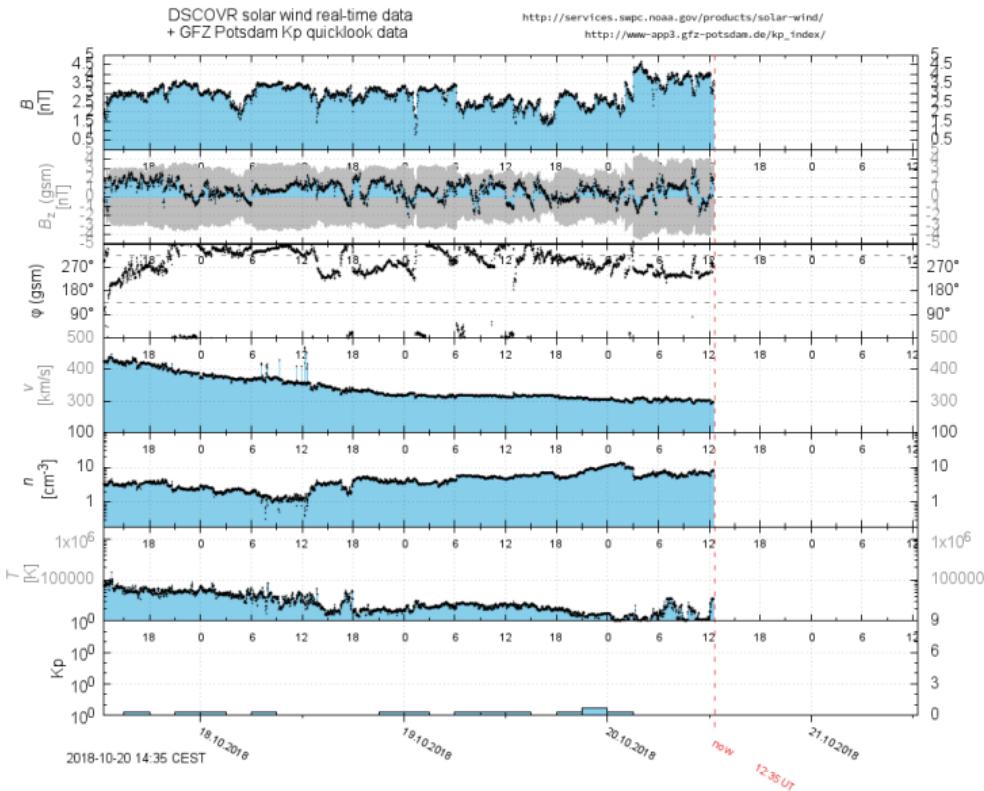
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Solar wind

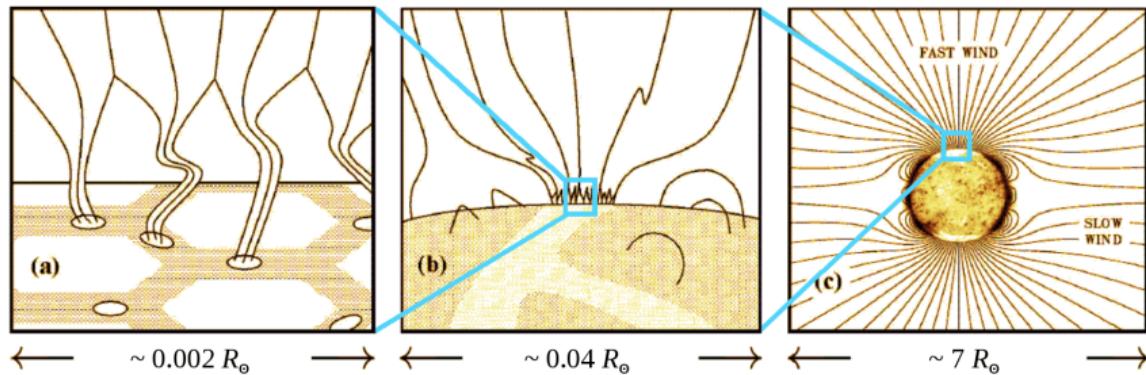
Geomagnetic impact of the solar wind  
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Solar wind model for the inner heliosphere  
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# Solar wind

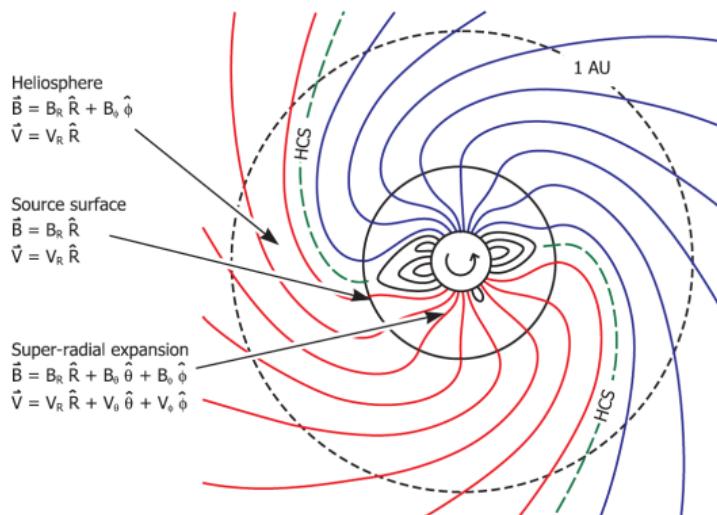


# Solar magnetic field



Courtesy of S. R. Cranmer

# Solar magnetic field



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

Backup slides

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Solar wind

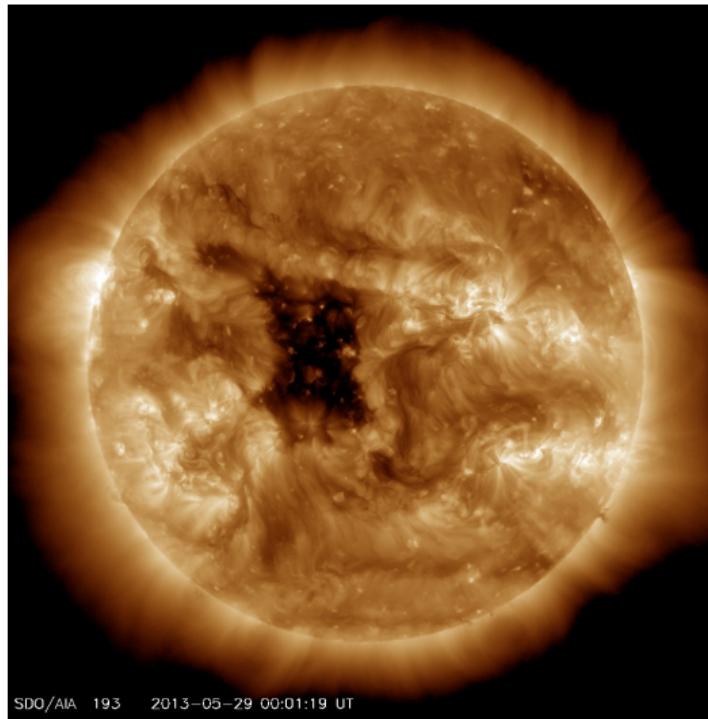
Geomagnetic impact of the solar wind

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Solar wind model for the inner heliosphere

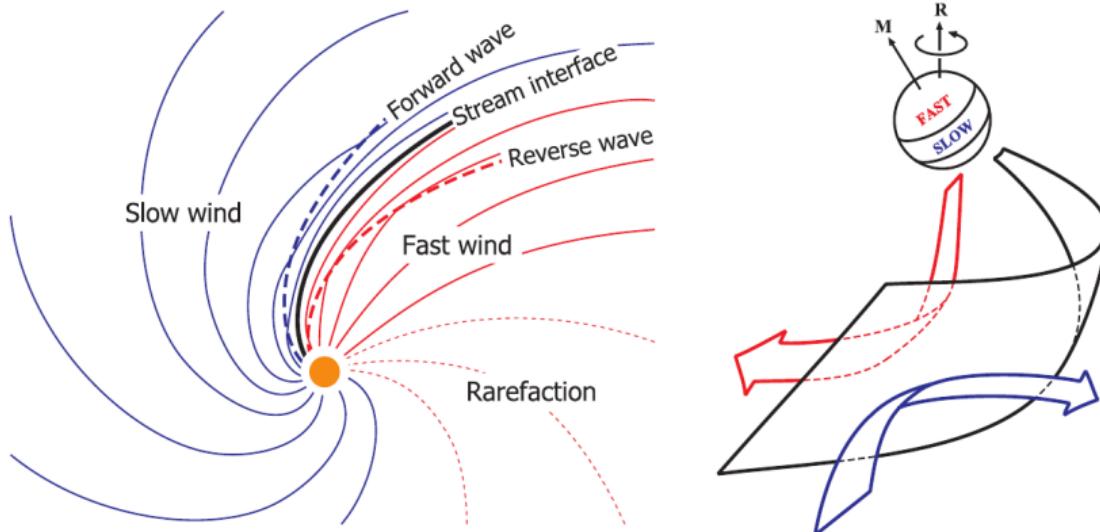
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## Slow and fast solar wind



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)

Backup slides  
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Solar wind

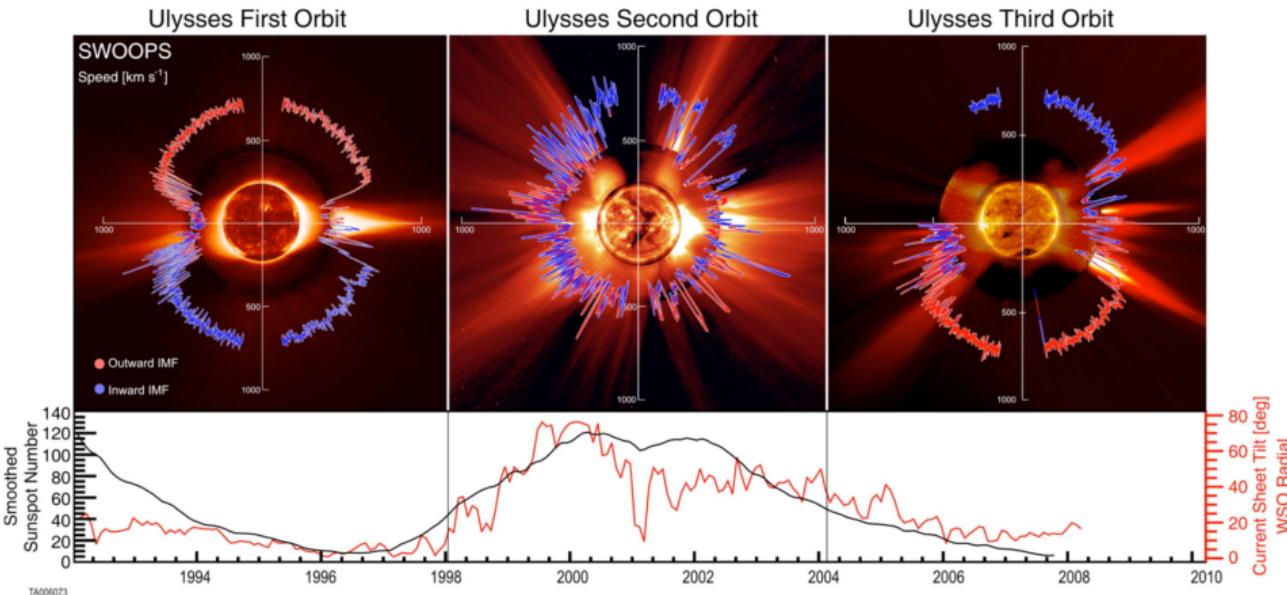
# Solar activity

## Sunspots

Geomagnetic impact of the solar wind  
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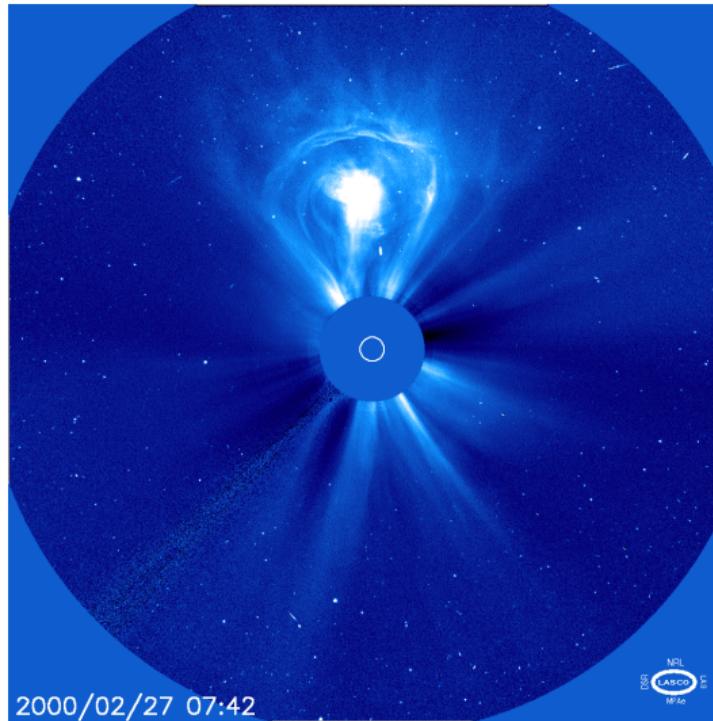
Solar wind model for the inner heliosphere  
oooooo

# 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

Backup slides

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Solar wind

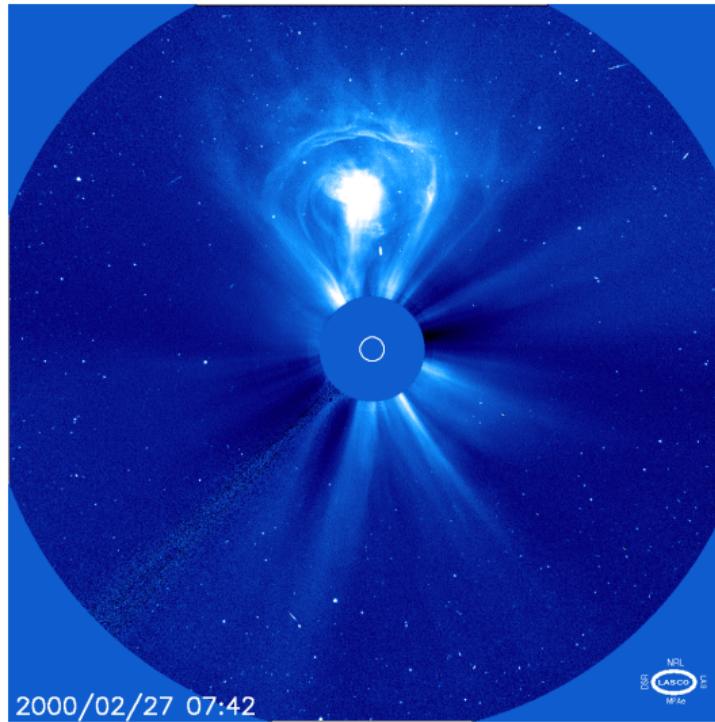
Geomagnetic impact of the solar wind

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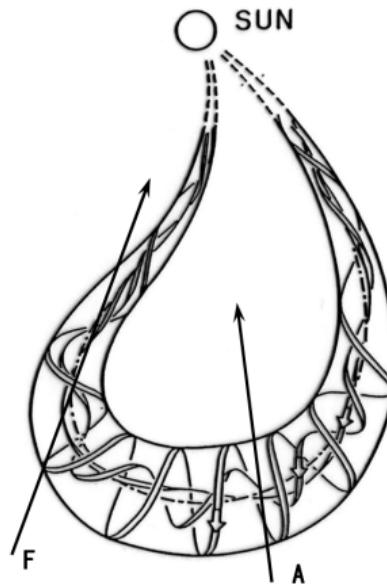
Solar wind model for the inner heliosphere

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## 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))

Backup slides

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Solar wind

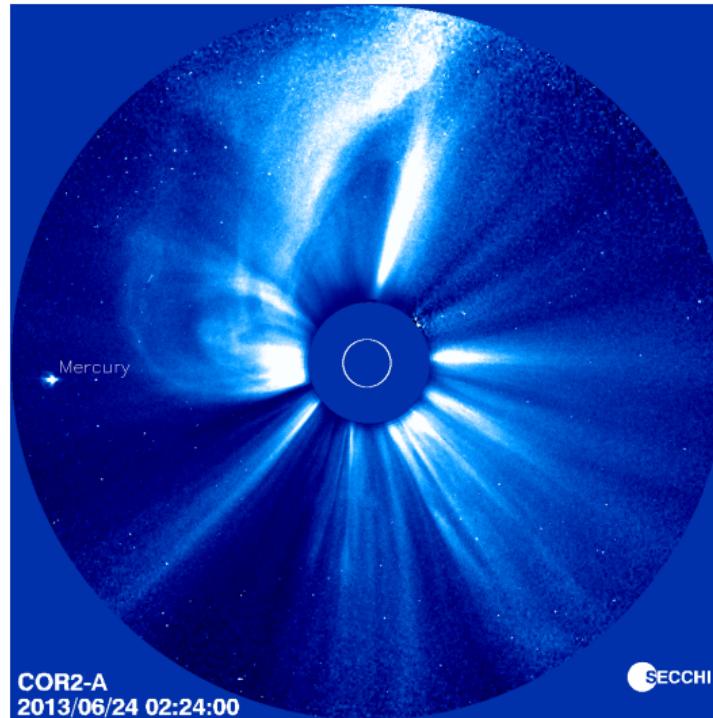
Geomagnetic impact of the solar wind

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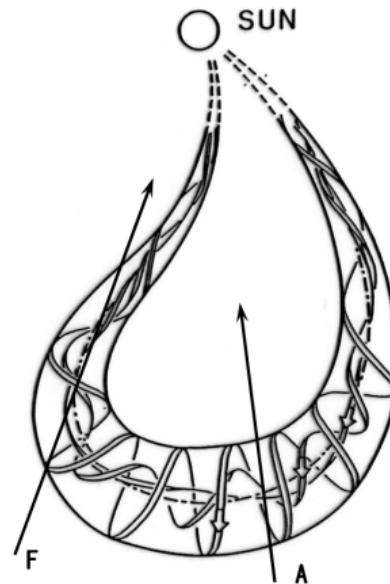
Solar wind model for the inner heliosphere

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## Coronal mass ejections

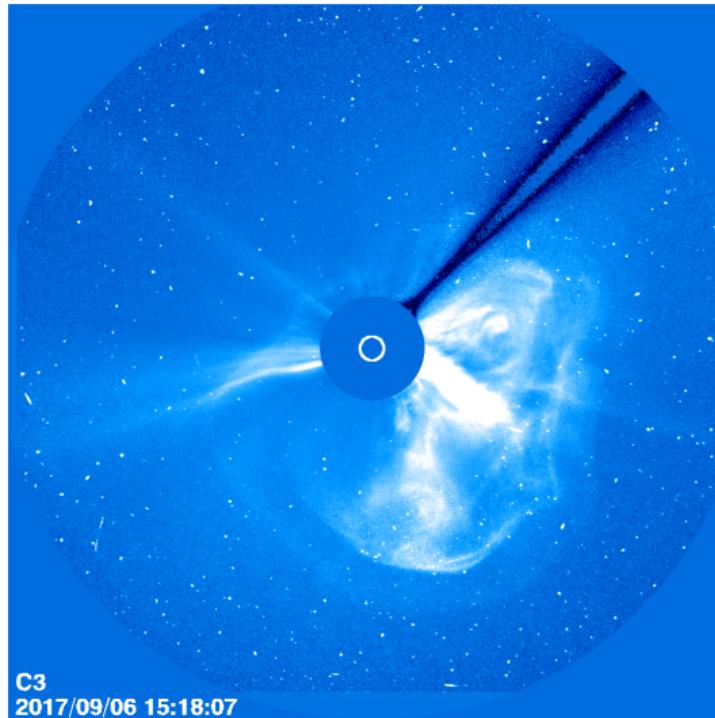


Courtesy of STEREO/COR2 consortium (NASA)



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

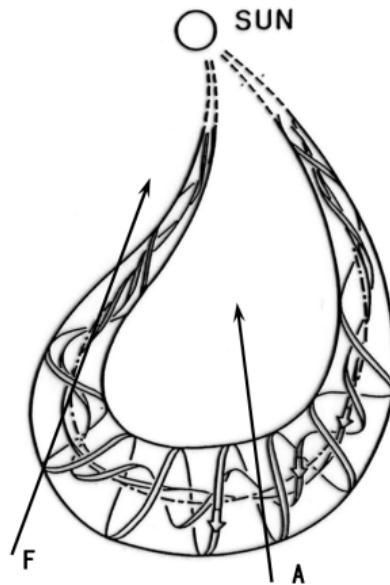
# Coronal mass ejections



C3

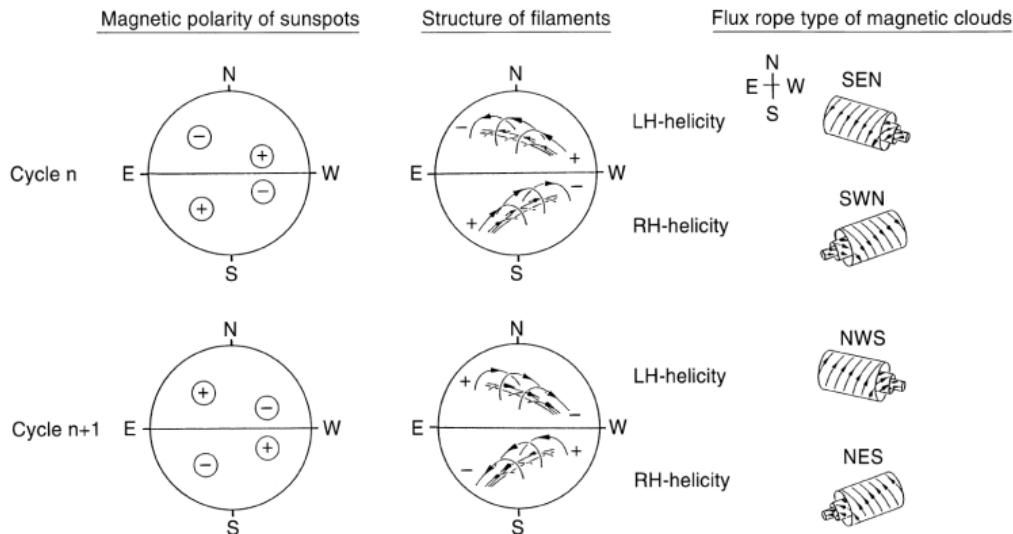
2017/09/06 15:18:07

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



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

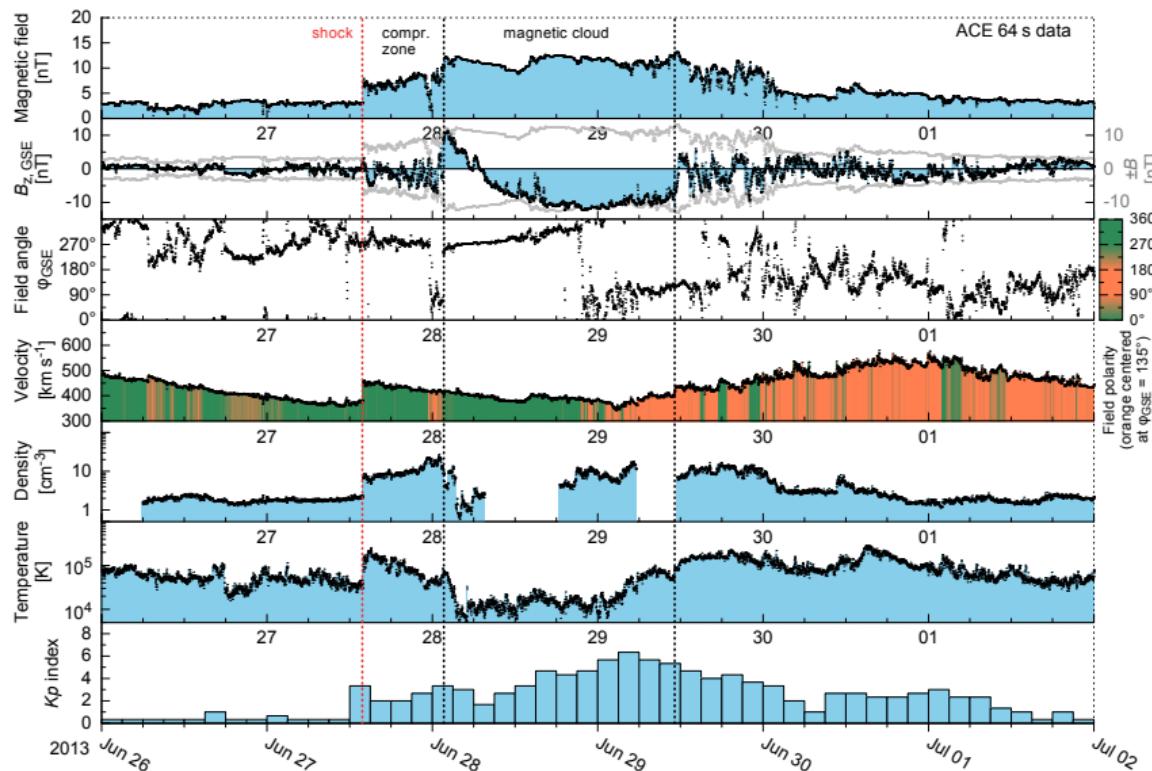
# CME orientation



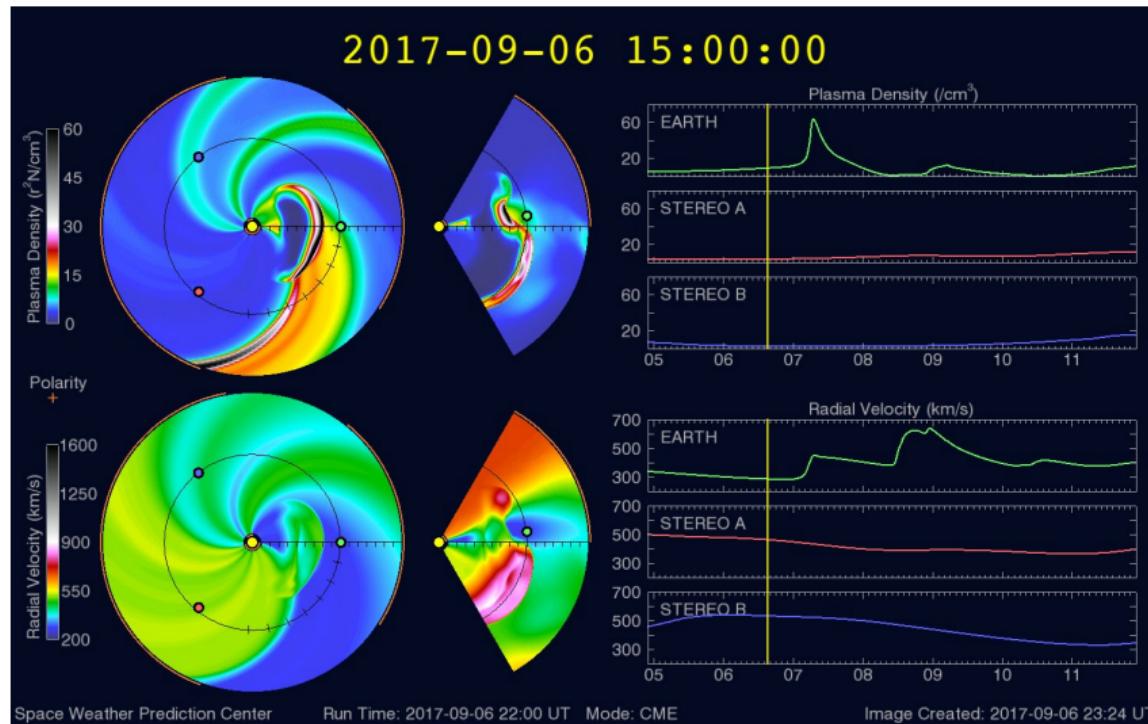
Credit: Bothmer & Schwenn (1998, Fig. 18)

Solar wind

# In-situ CMEs

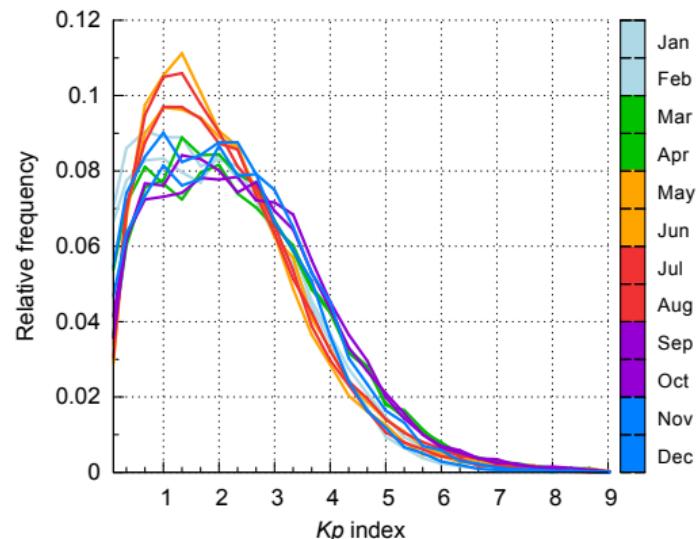
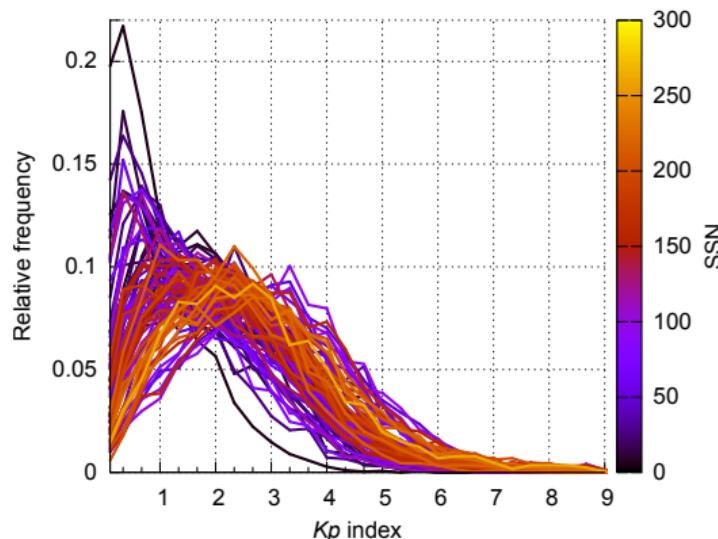


# Solar wind and CME forecast

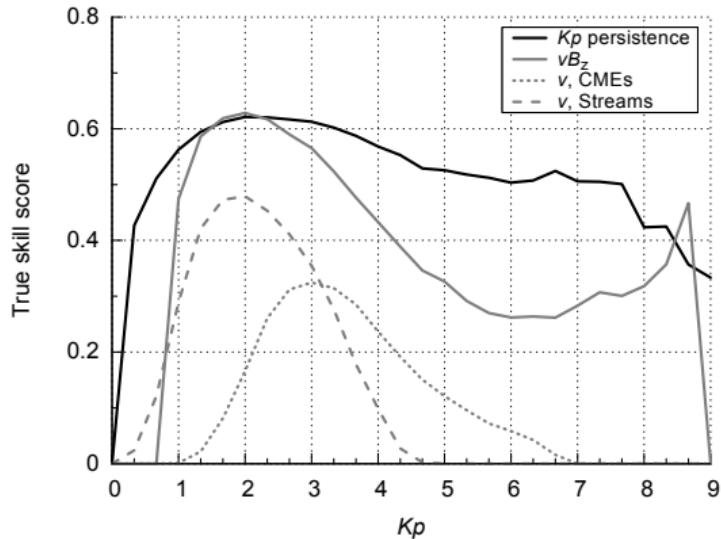
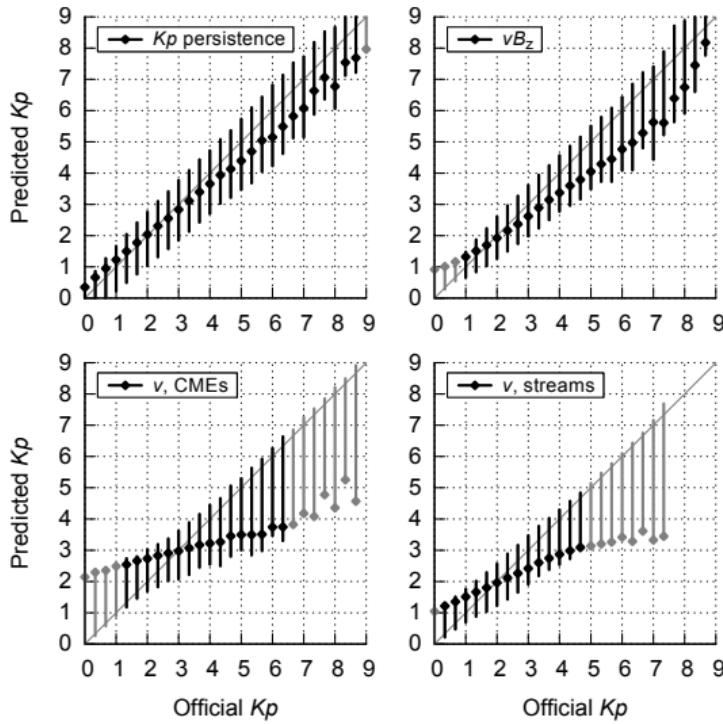


Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

# K<sub>p</sub> long-term variations



# Prediction performance

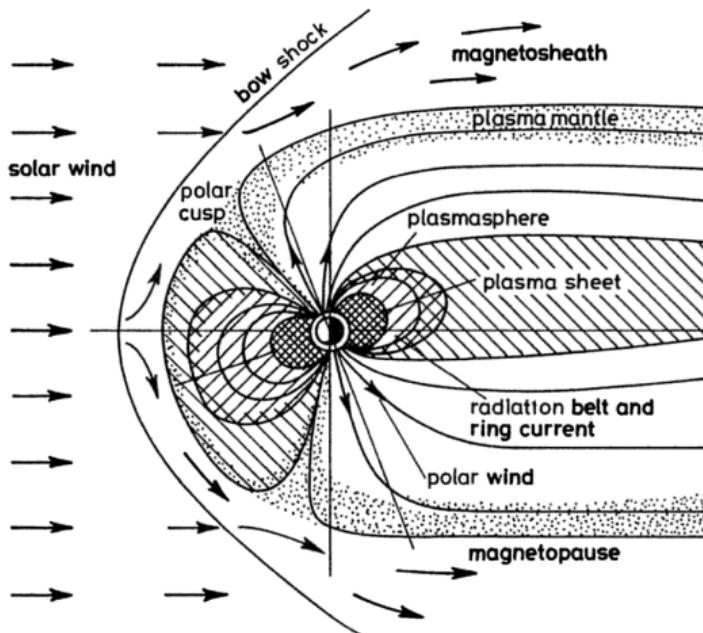


# Geomagnetic impact of the solar wind

## Aims

Empirical relations to predict the  $K_p$  index from solar wind electric field and from CME and stream velocity

# Magnetosphere



Credit: Davies (1990, Fig. 2.12)

Backup slides  
ooooooooooooooo

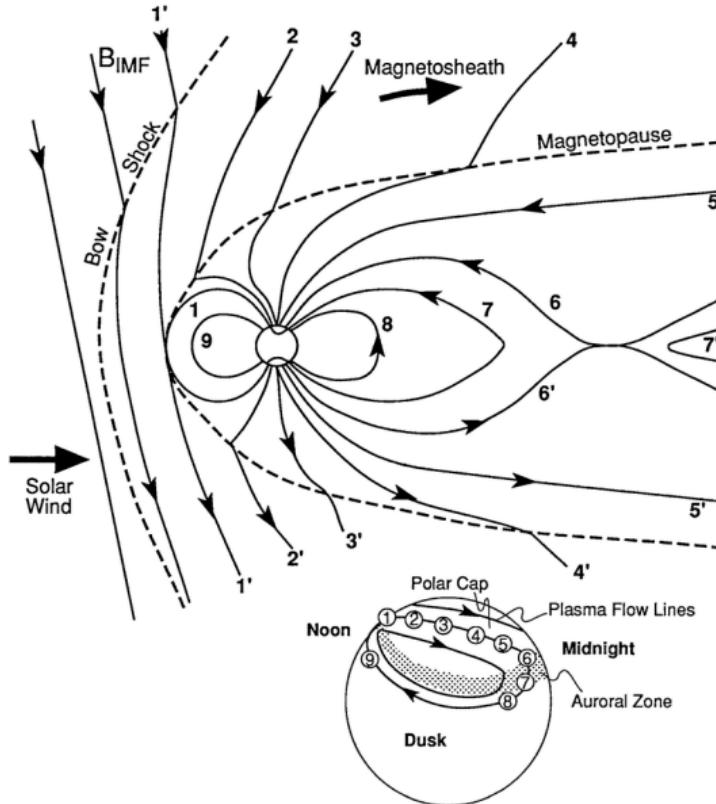
Geomagnetic impact of the solar wind  
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Solar wind model for the inner heliosphere  
oooooo

# Magnetosphere

4 interaction mechanisms

# Magnetosphere



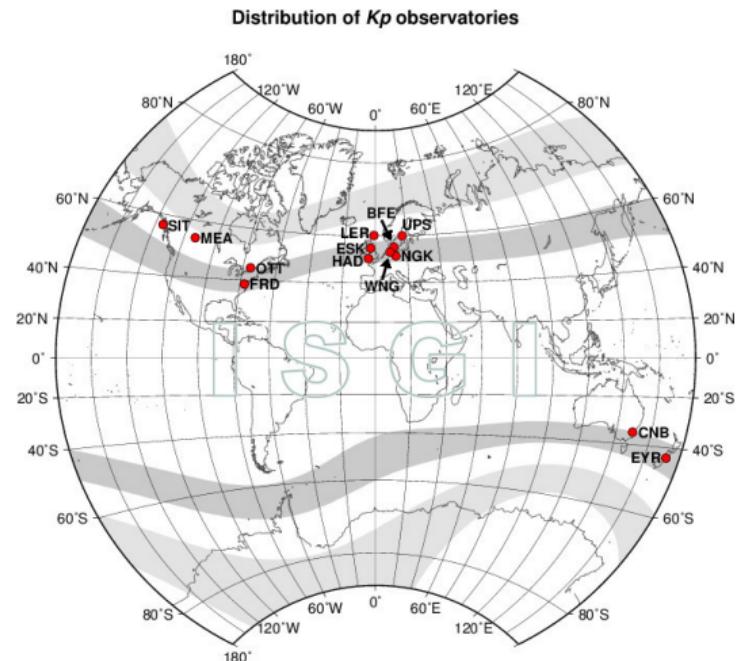
Credit: Hughes (1995, Fig. 9.11)

# Magnetosphere

4 factors for merging flux rate

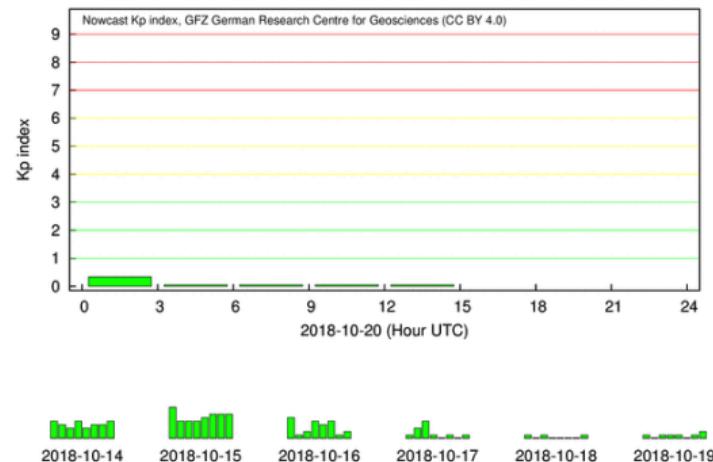
# K<sub>p</sub> index

13 observatories...



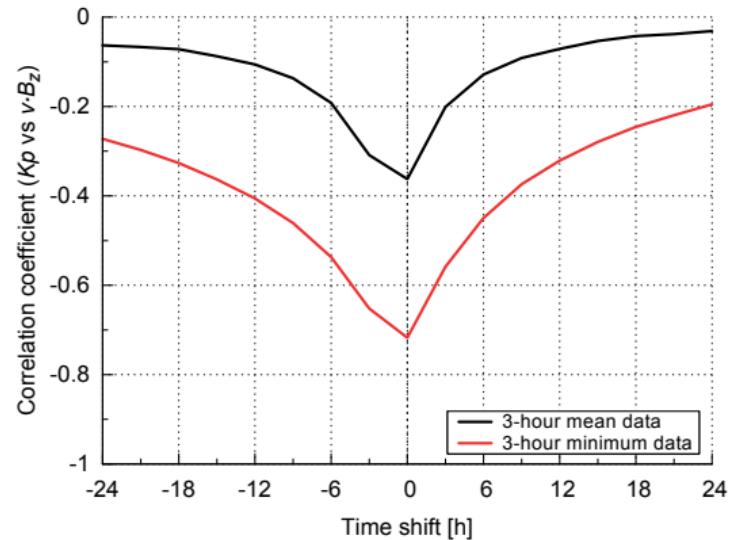
# *K<sub>p</sub>* index

## Quicklook *K<sub>p</sub>*

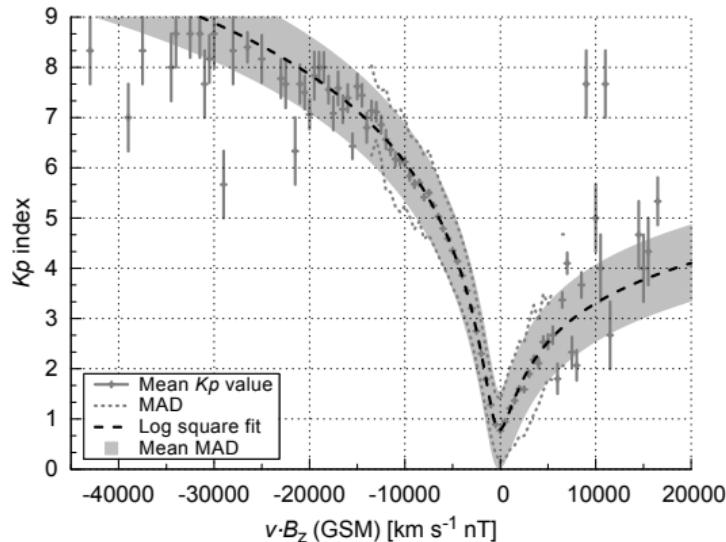
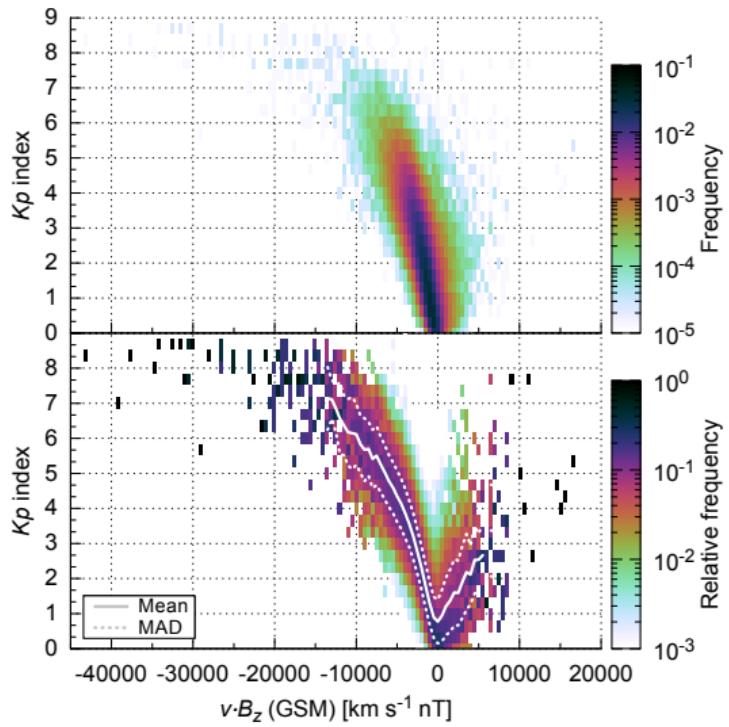


Credit: GFZ Potsdam, 2018

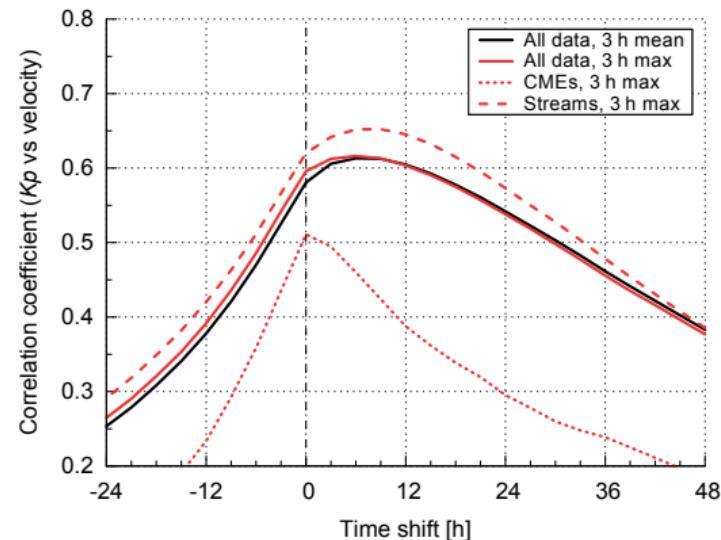
# Solar wind electric field



# Solar wind electric field



## Solar wind velocity



Backup slides  
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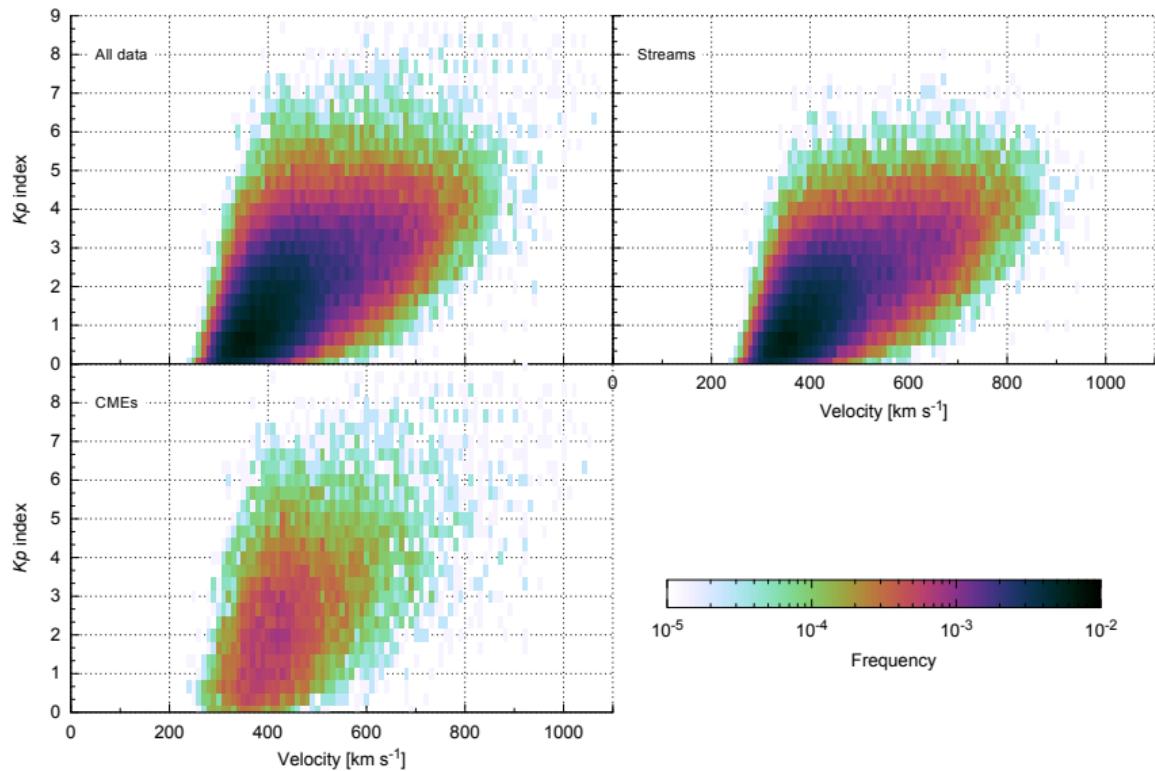
Geomagnetic impact of the solar wind  
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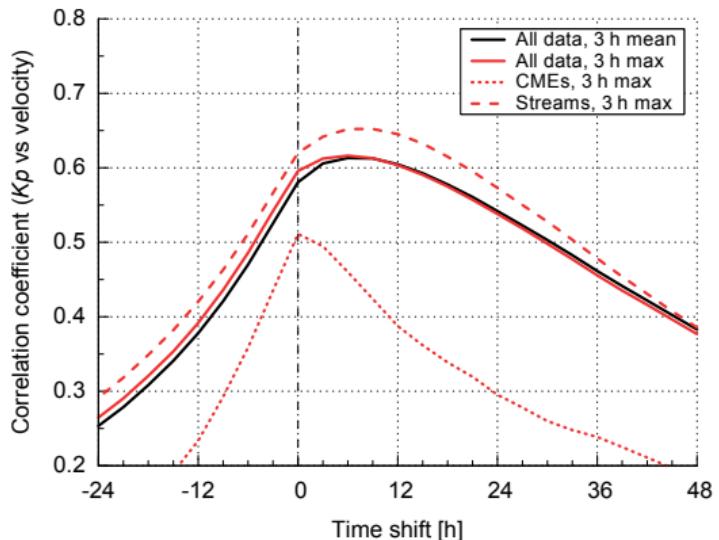
Solar wind model for the inner heliosphere  
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## Solar wind velocity

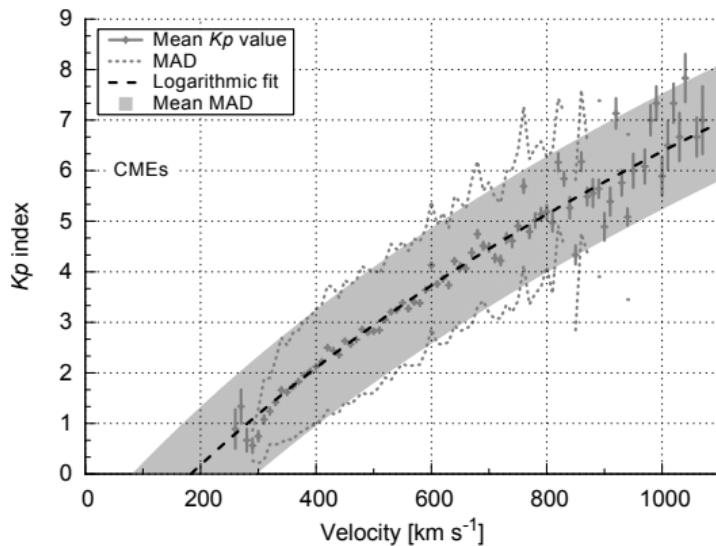
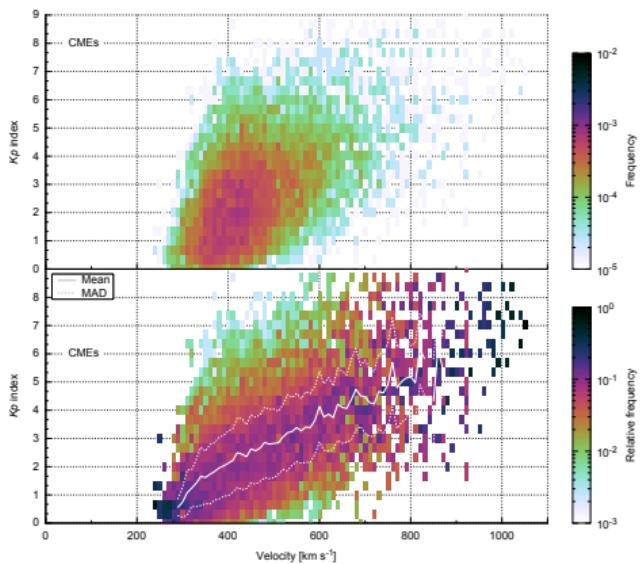
CME – stream separation  
Solar Wind Structures list

# Solar wind velocity

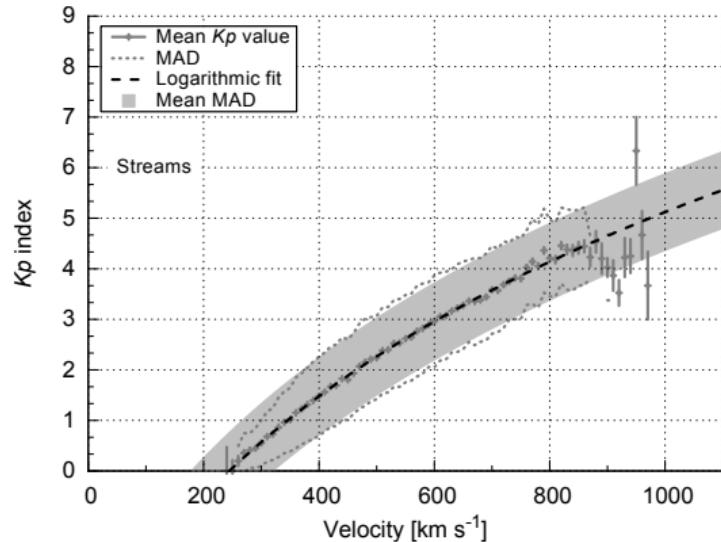
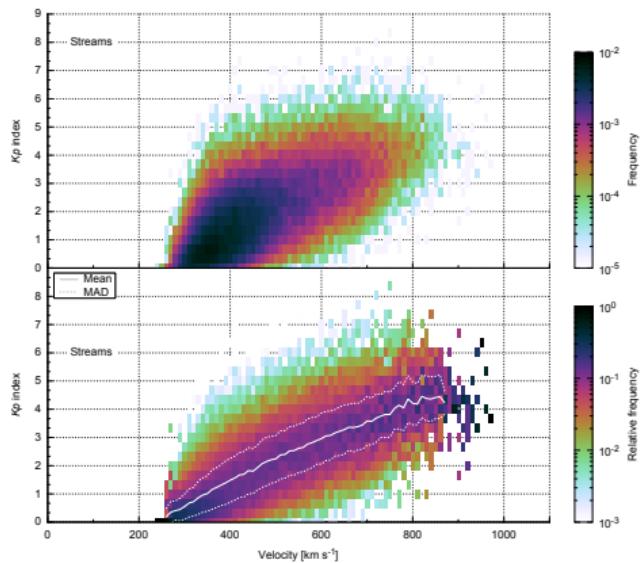


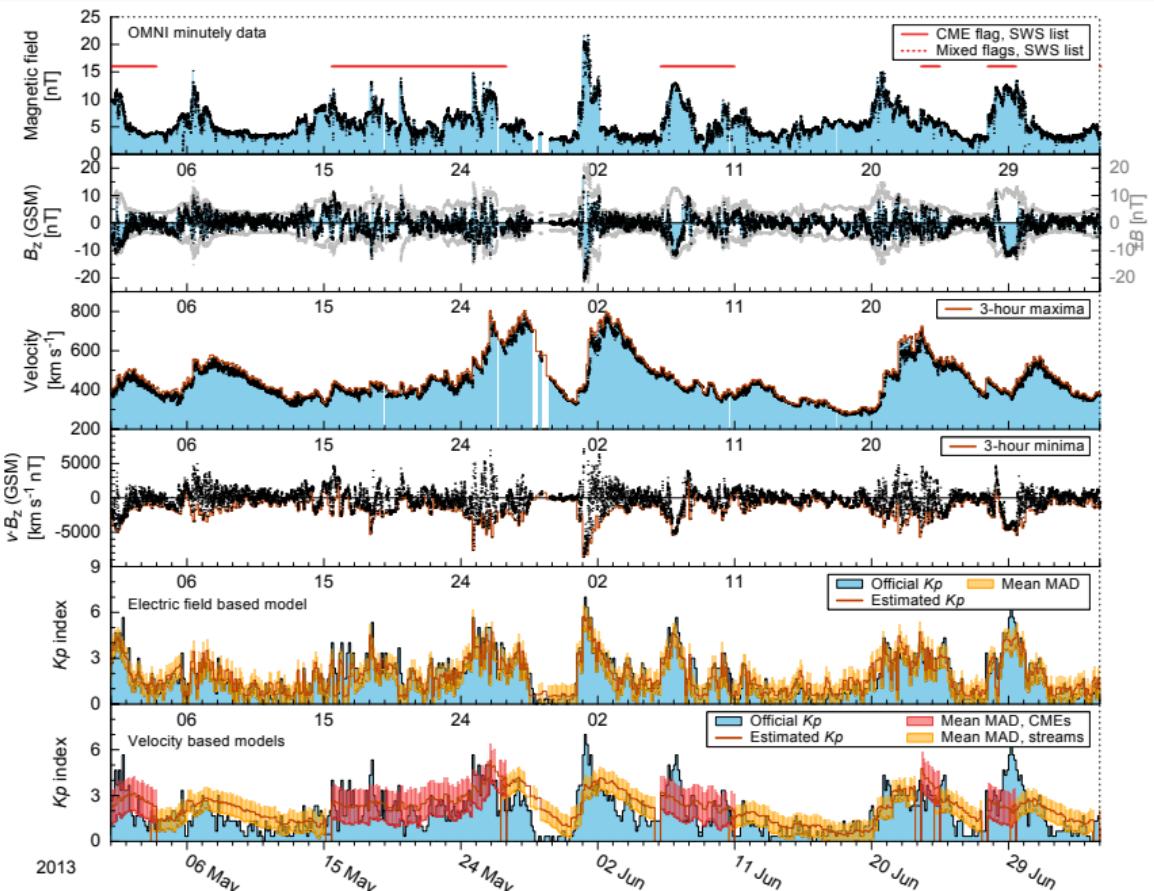


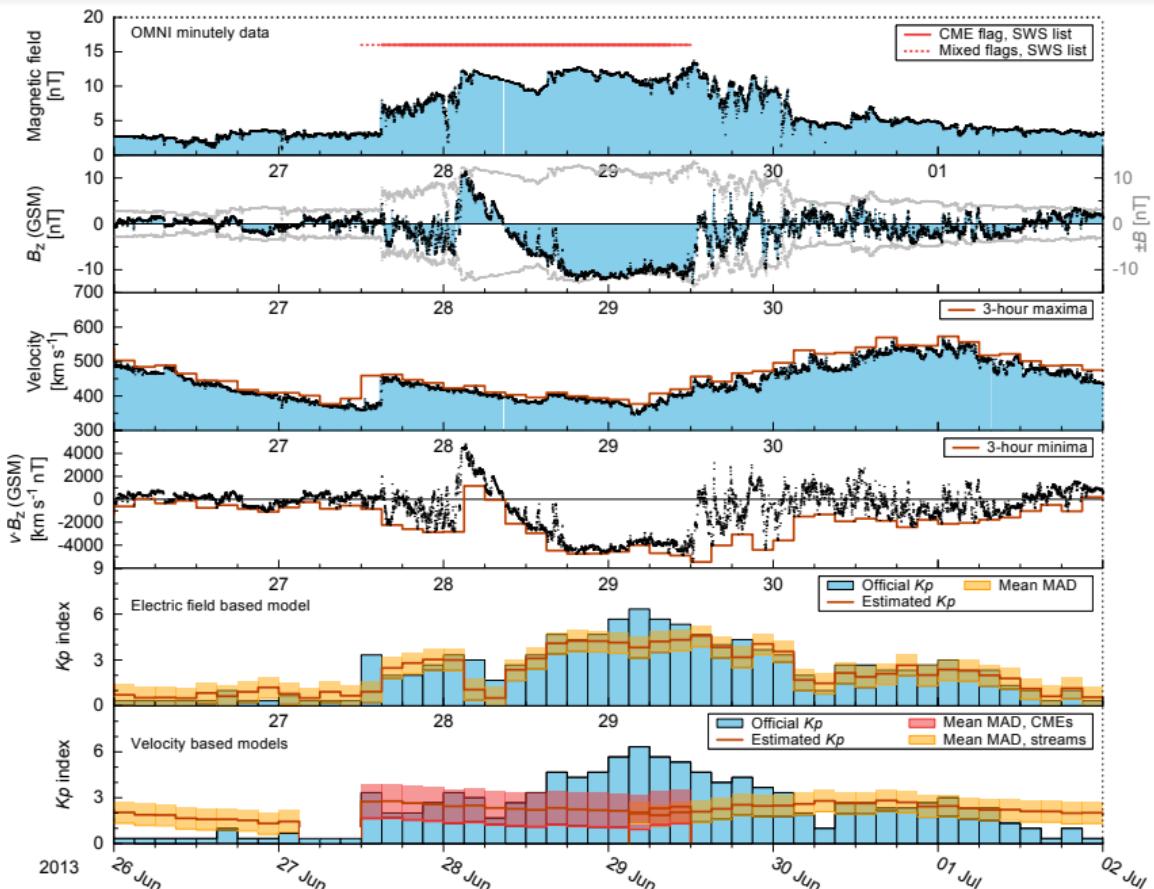
# CME velocity



# Stream velocity







# Results

Predictive  $K_p$  models based on relations with

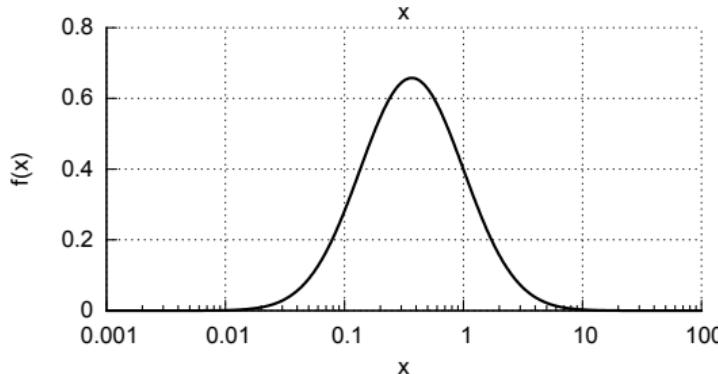
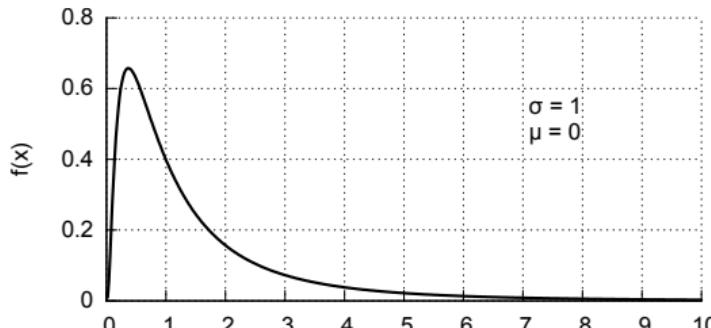
- solar wind electric field proxy ( $vB_z$ )
- velocity of CME-associated flows ( $v_{\text{CME}}$ )
- velocity of solar wind streams ( $v_{\text{stream}}$ )

## 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

# 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 ( $\sigma$ )

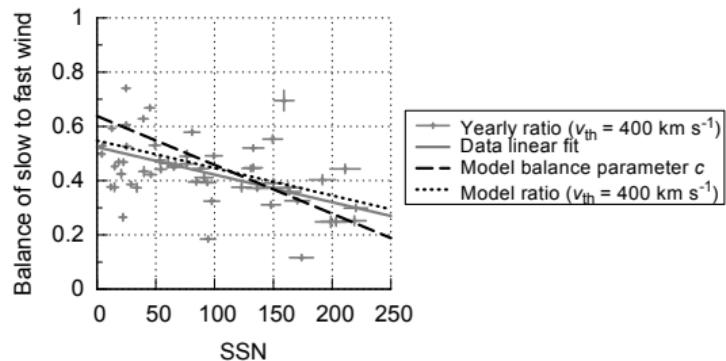
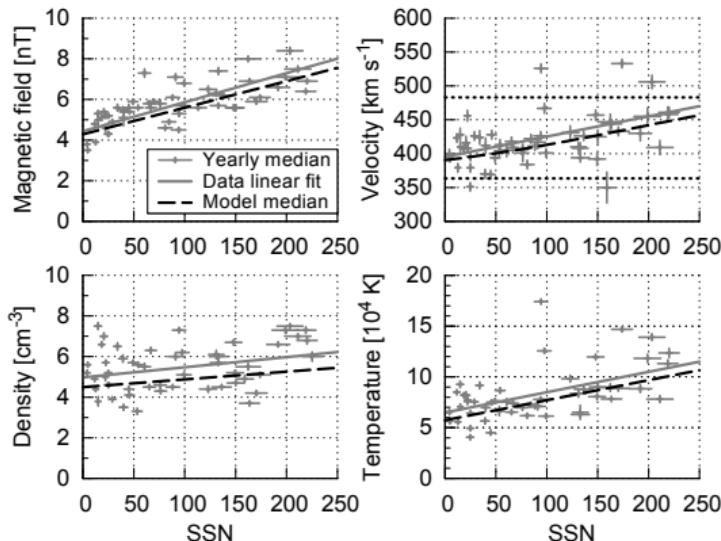
## Sun–Earth evolution of the solar wind

Solar wind measured in-situ throughout the heliosphere – except near-Sun

# Sun–Earth evolution of the solar wind

special scientific interest:  
coronal heating  
solar wind acceleration

# Solar activity



# Sun–Earth evolution of the solar wind

## Aims

Solar wind model for the inner heliosphere and prediction of the near-Sun environment  
for the PSP orbit

Backup slides  
ooooooooooooooo

Geomagnetic impact of the solar wind  
oooooooooooooooooooo

Solar wind model for the inner heliosphere  
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combine models, extrapolation

# PSP perihelia prediction

