

# 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)



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## 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 – Predictive models for space weather

- Brief summary

### Solar wind model – Predictions for the Parker Solar Probe orbit

- Intro
- Parker Solar Probe
- Solar wind model
- Prediction for PSP orbit

# 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

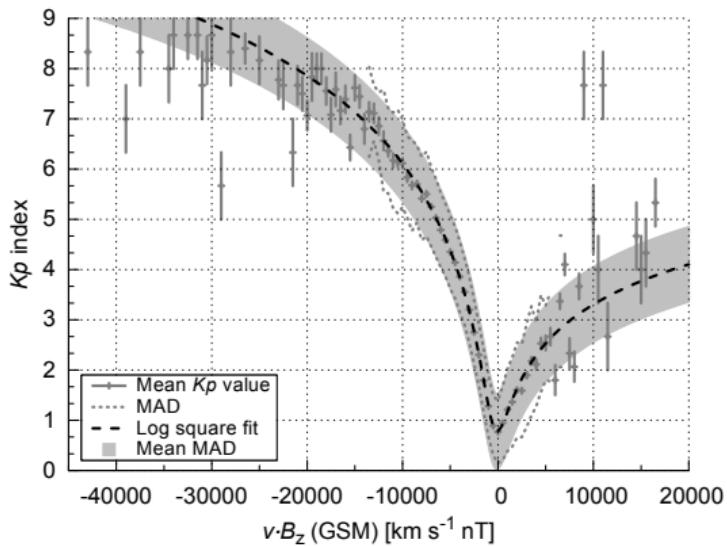
# Geomagnetic impact of the solar wind

*Kp* index  
coupling mechanisms  
reconnection at magnetopause

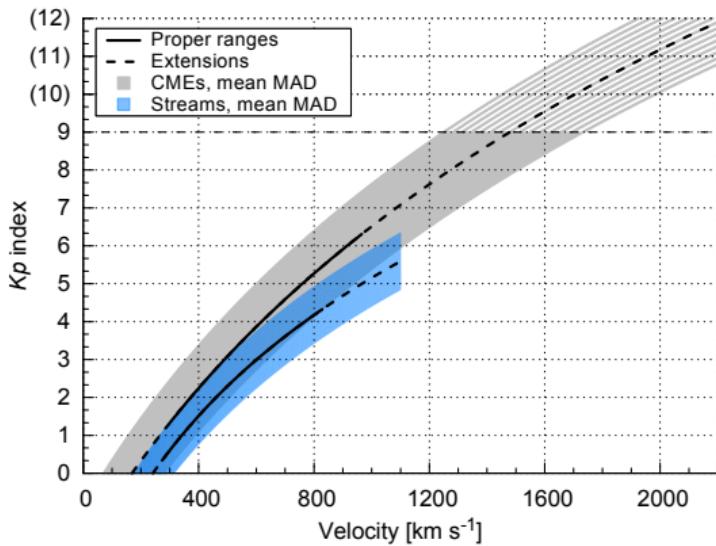
# Geomagnetic impact of the solar wind

Relations between the  $K_p$  index and solar wind parameters:

Electric field proxy ( $vB_z$ )



Velocity of CMEs and streams



# 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



Total Solar Eclipse 2017

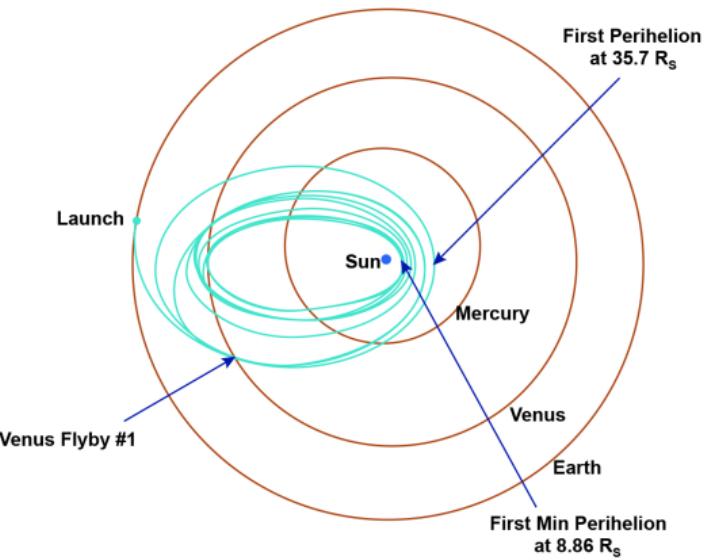
© 2017 Miloslav Druckmüller, Zuzana Druckmüllerová, Jana Hoderová, Petr Štarha, Shadia Habbal

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

# Parker Solar Probe



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  
( $9.86 R_{\odot}$ )

## 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

## 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

## Model concept

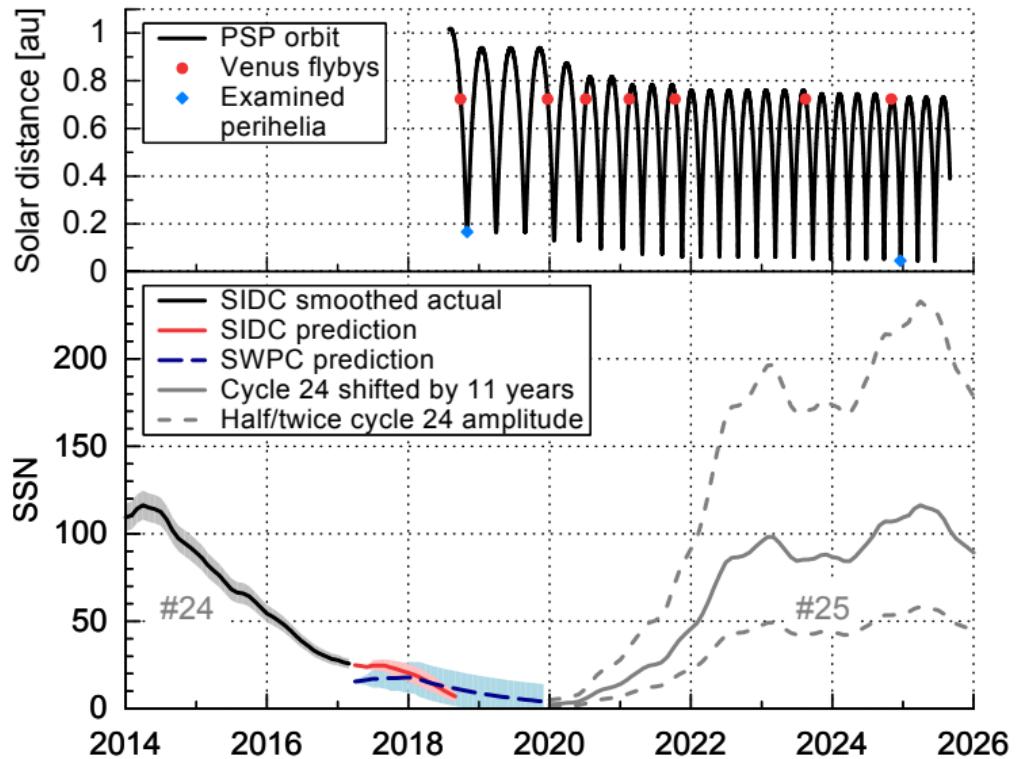
### Solar wind key parameters

- Magnetic field strength
- Velocity
- Density
- Temperature

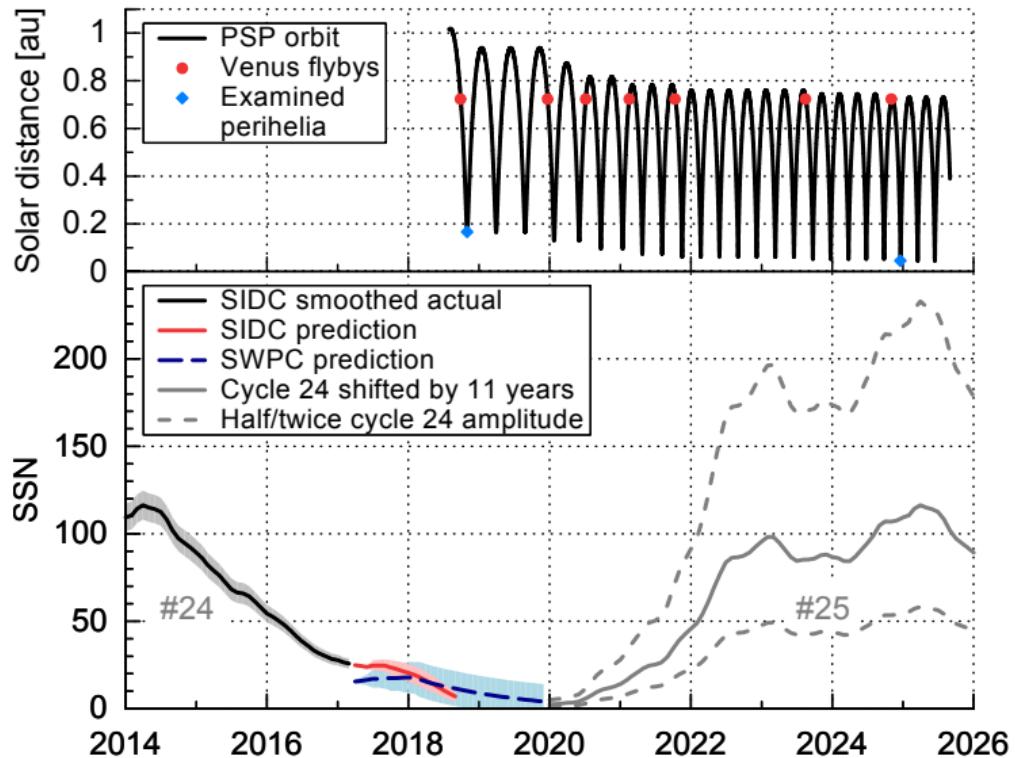
values shifted according to solar activity and solar distance

unique: frequency distributions

# PSP distance and SSN prediction



# PSP distance and SSN prediction

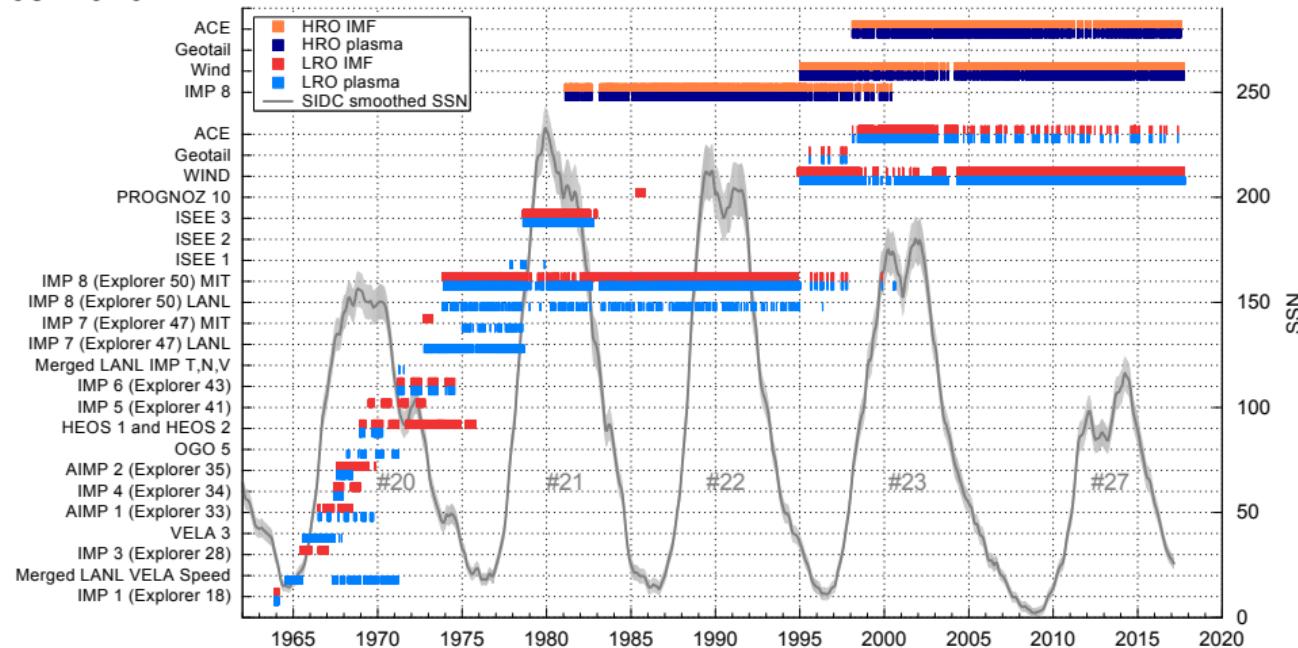


2018: solar minimum  
2024: solar maximum

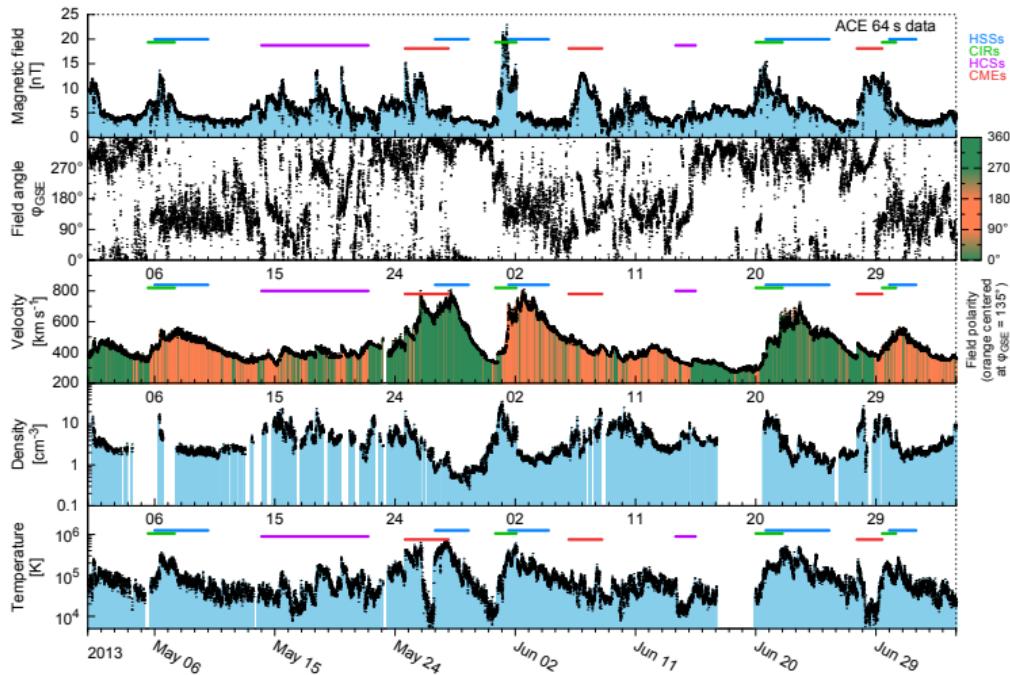
# OMNI data set

OMNI data set (King & Papitashvili, 2005)

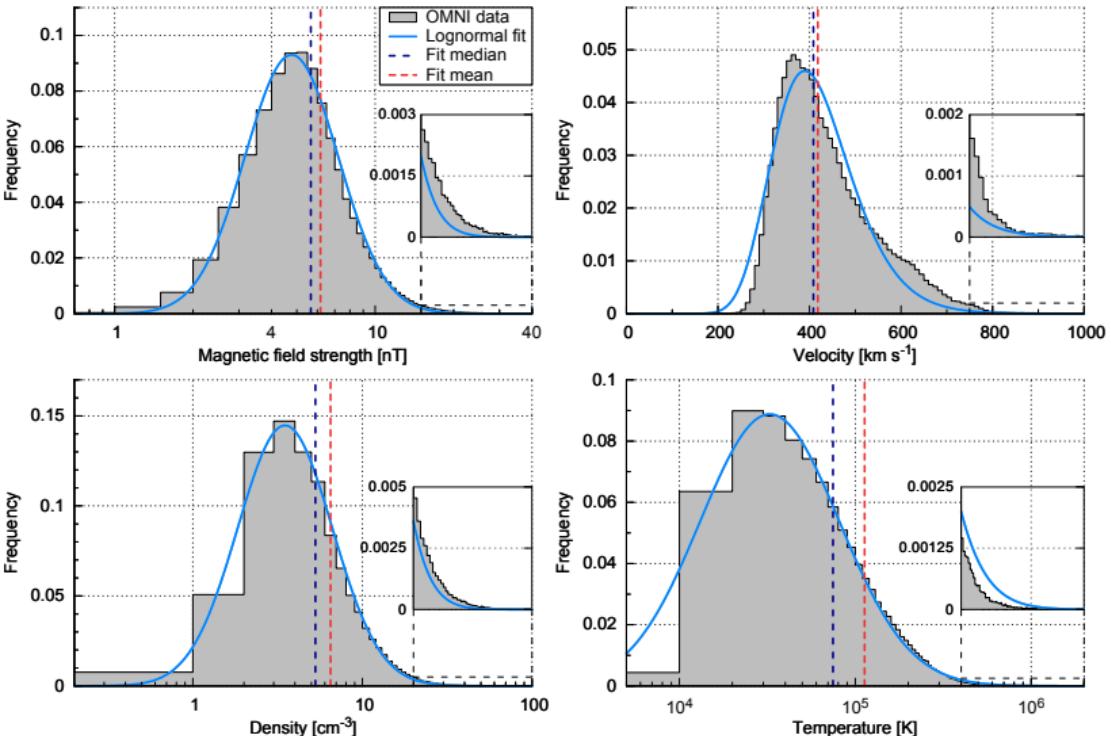
- intercalibrated multi-spacecraft data
- time-shifted to the bow shock of the magnetosphere
- 1963–2016



# OMNI data set

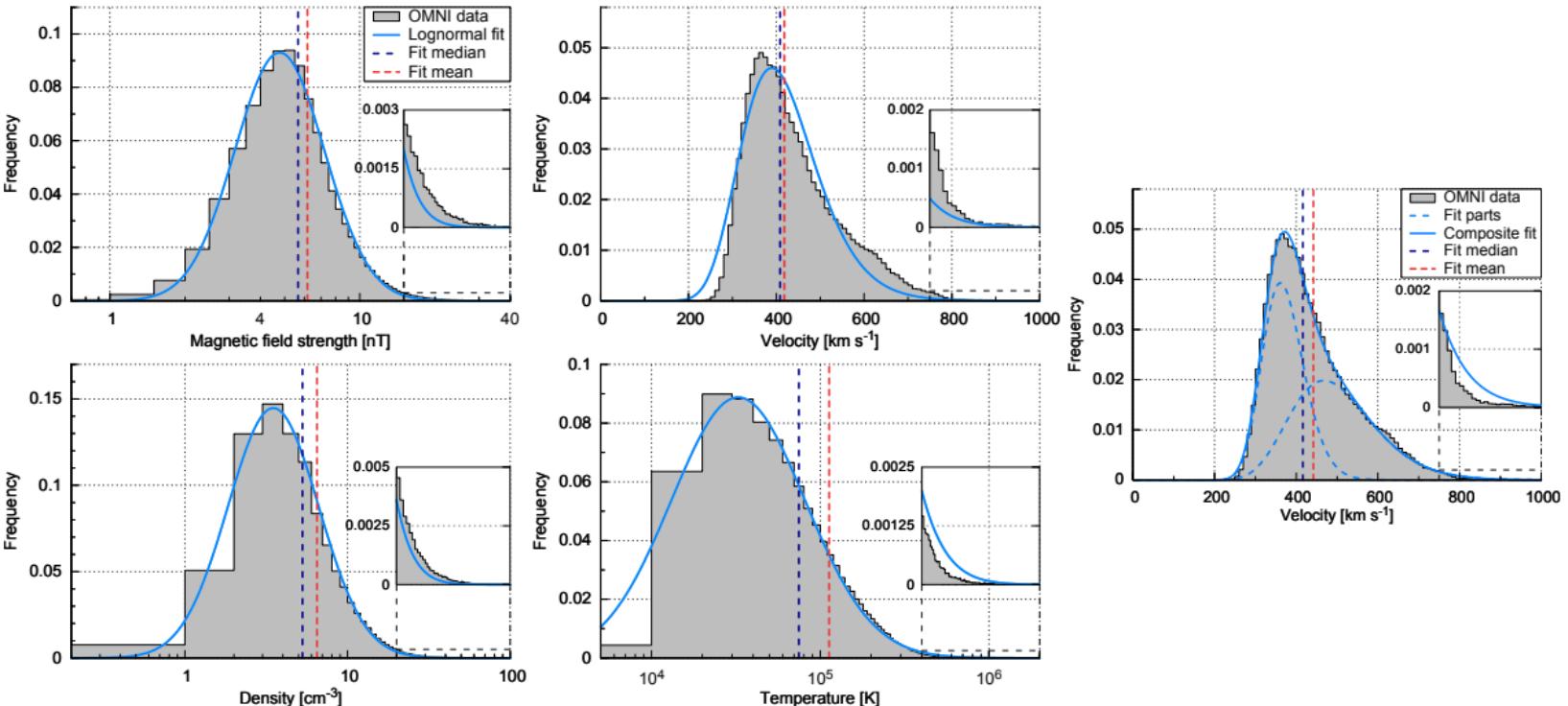


# Frequency distributions



» Lognormal distribution

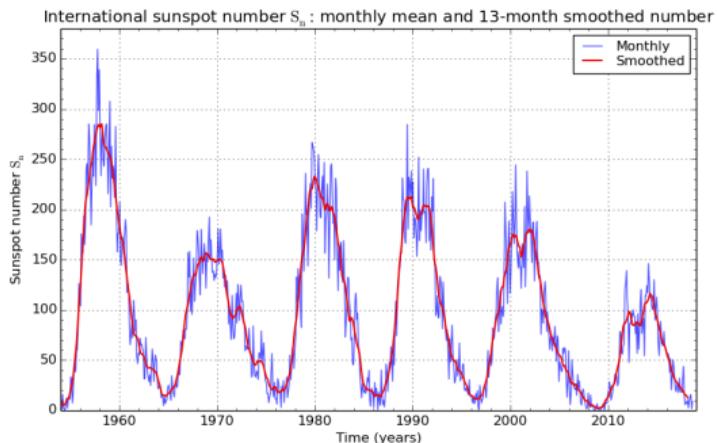
# Frequency distributions



» Lognormal distribution

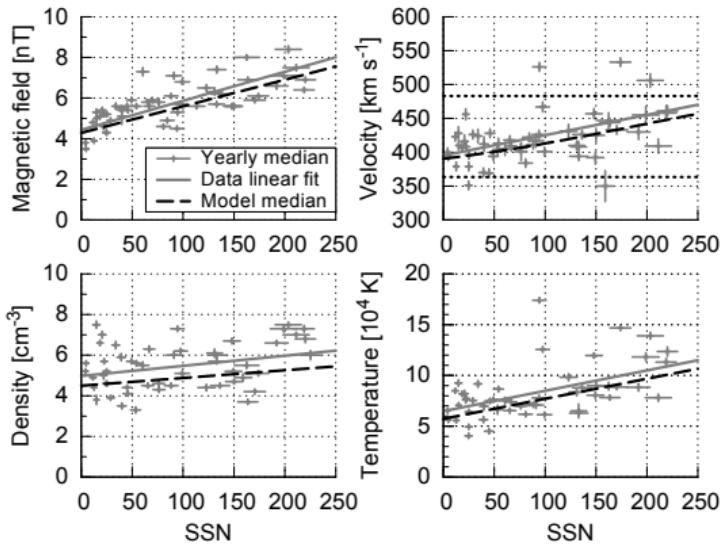
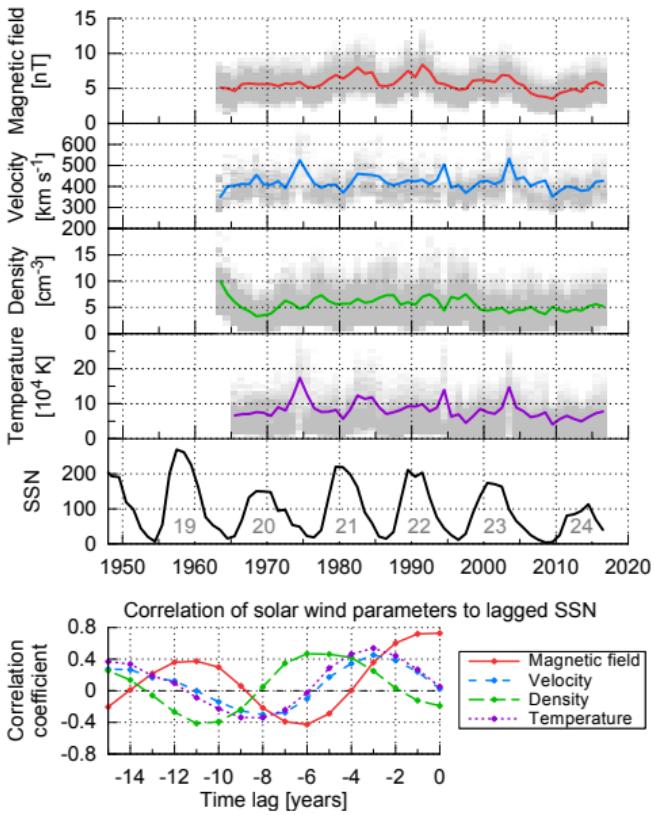
# Solar activity

sunspot images...

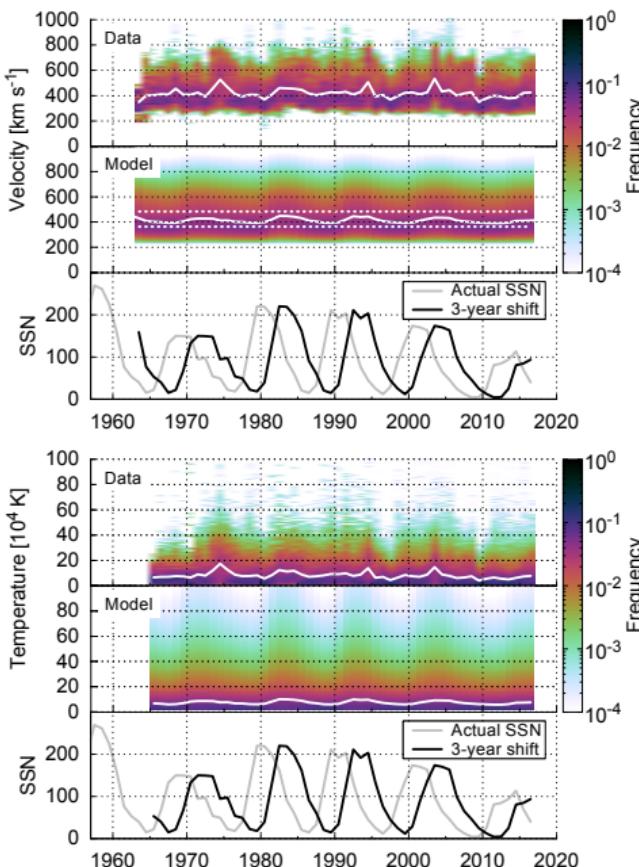
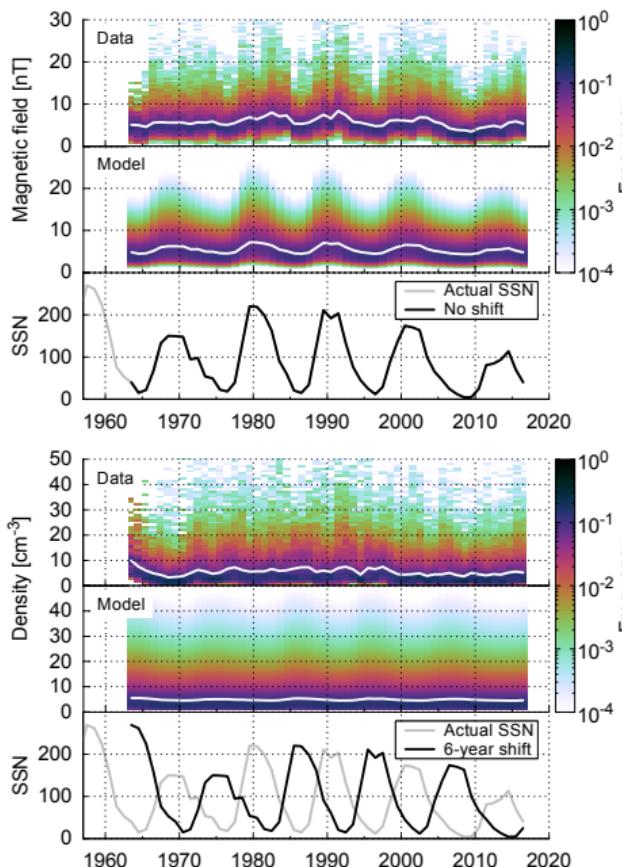


» Magnetic butterfly diagram

# Solar activity



# Solar activity

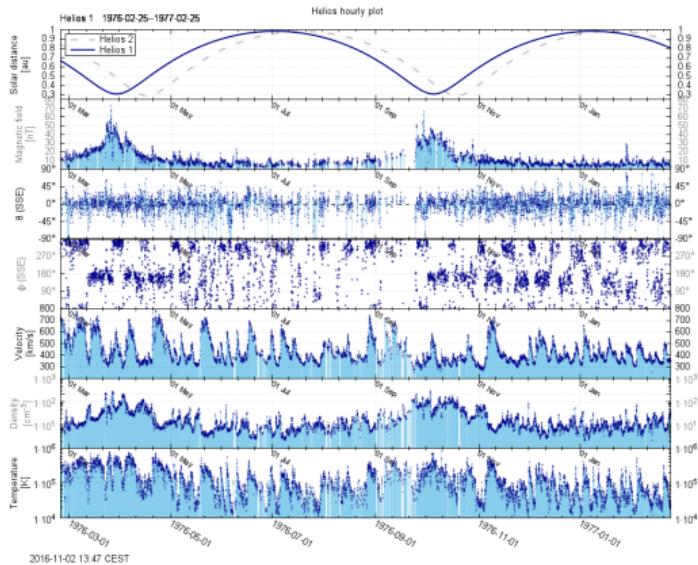


# Helios data

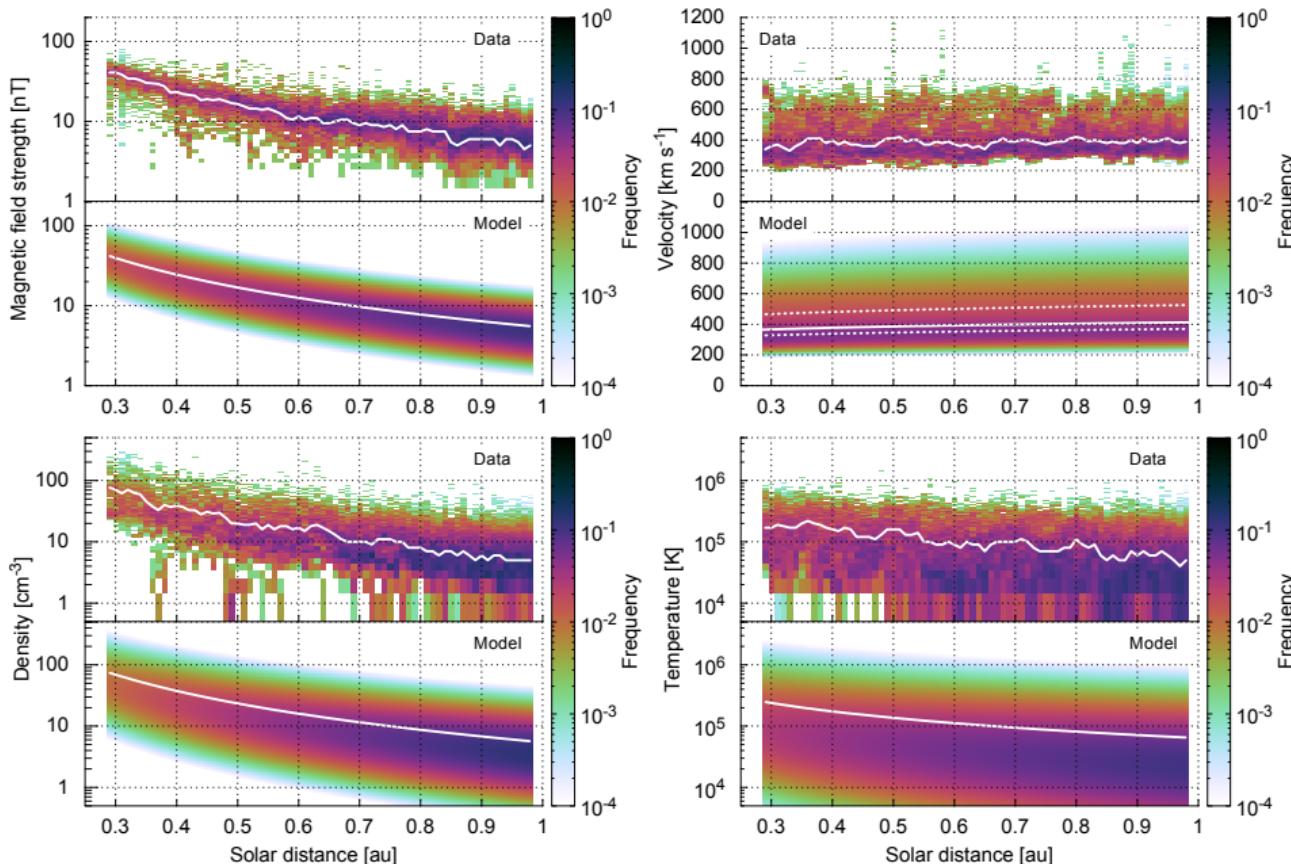


Credit: NASA

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

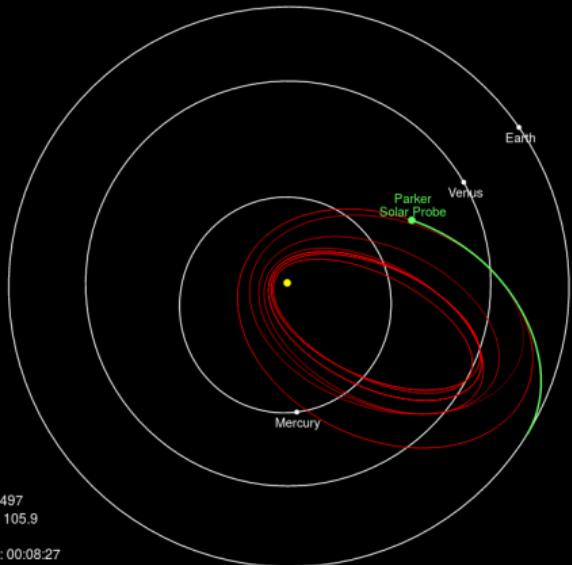


# Solar distance



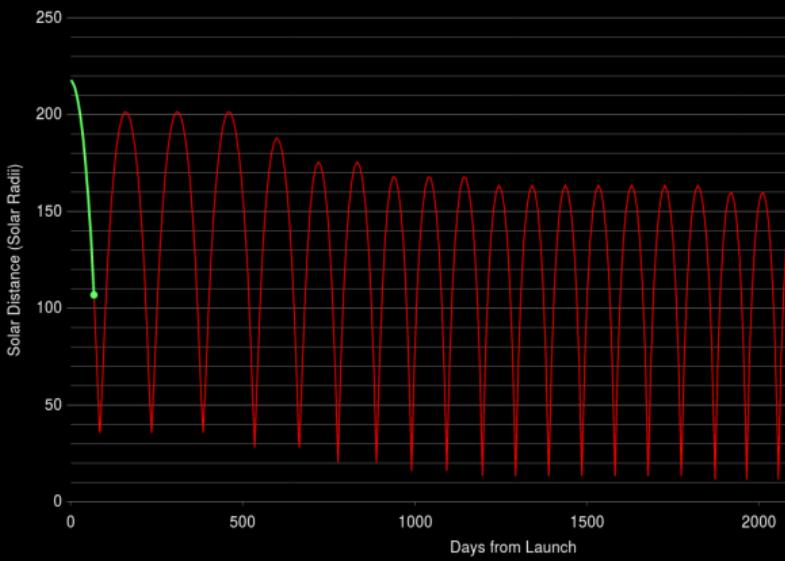
# PSP's current position

Parker Solar Probe Mission Trajectory and Current Position



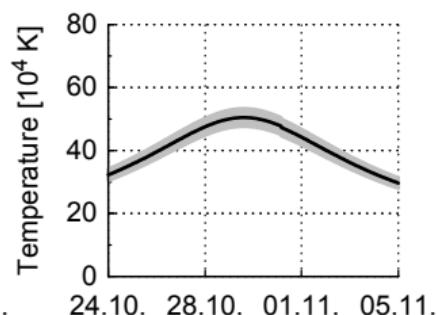
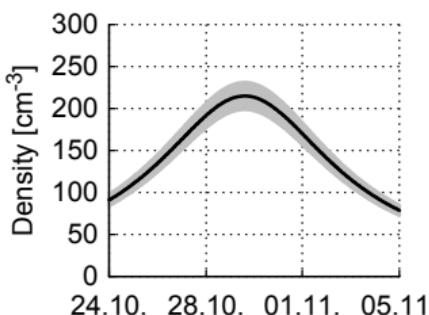
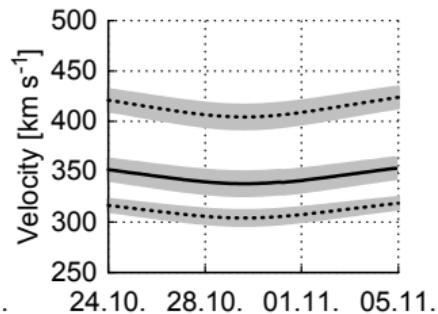
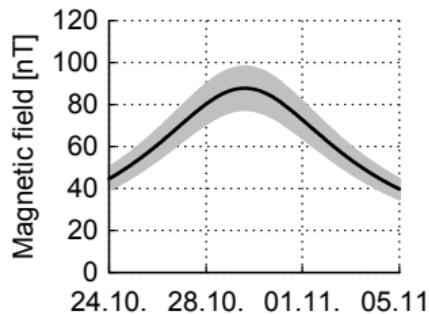
Credit: NASA

Parker Solar Probe Distance from Sun



# Prediction for PSP orbit

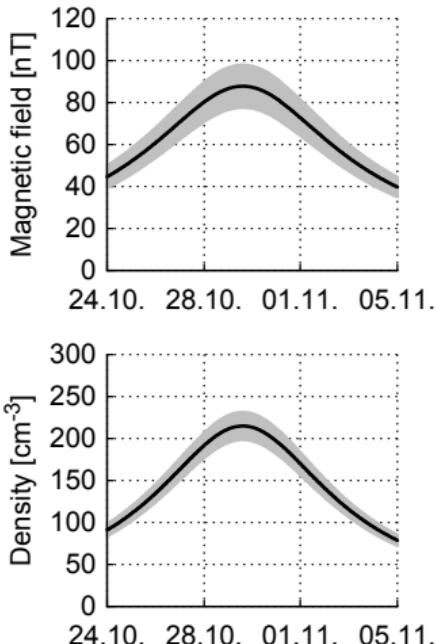
Perihelion #1



November 2018

# Prediction for PSP orbit

Perihelion #1



November 2018

Predicted values at  $36.7 R_{\odot}$

$$B = 94 \text{ nT}$$

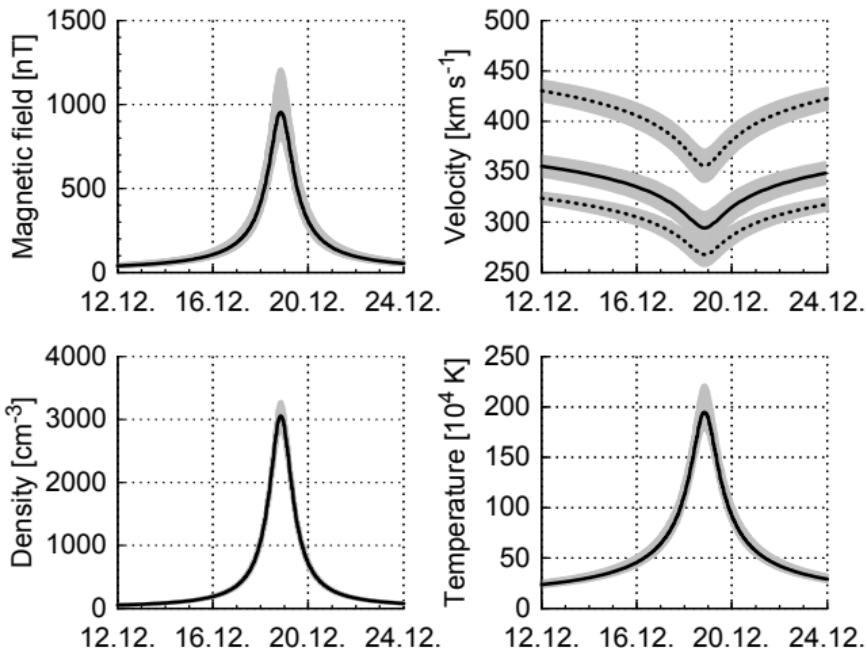
$$v = 340 \text{ km s}^{-1}$$

$$n = 214 \text{ cm}^{-3}$$

$$T = 5.03 \times 10^5 \text{ K}$$

# Prediction for PSP orbit

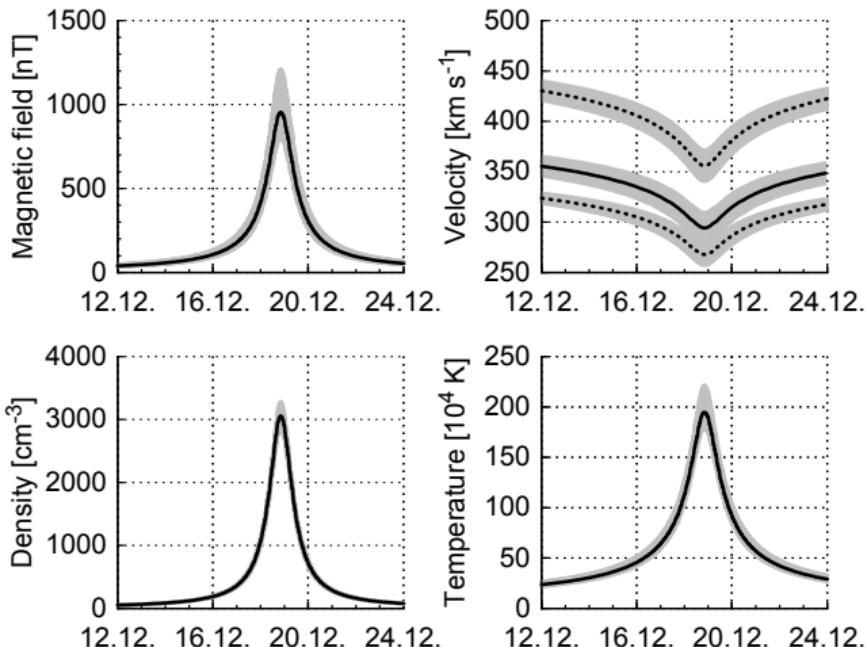
Perihelion #22 (first closest)



December 2024

# Prediction for PSP orbit

Perihelion #22 (first closest)



December 2024

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 values at $9.86 R_{\odot}$

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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

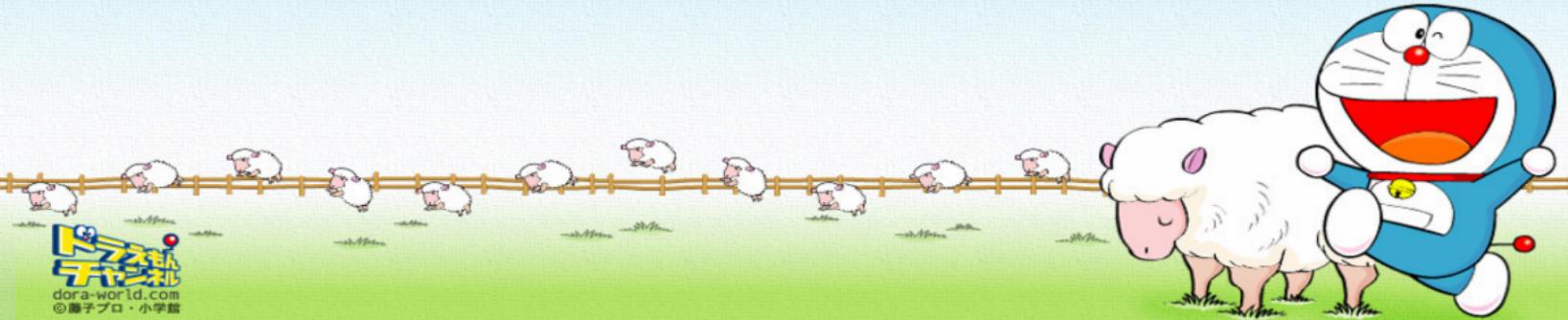
- Predictive models that relate geomagnetic disturbances with specific solar wind parameters:
  - Solar wind electric field
  - CME velocity
  - Stream velocity
- Empirical solar wind model for the inner heliosphere that considers solar activity and solar distance
  - Extrapolation of the model to the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

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Thank you!



Backup slides



Solar wind

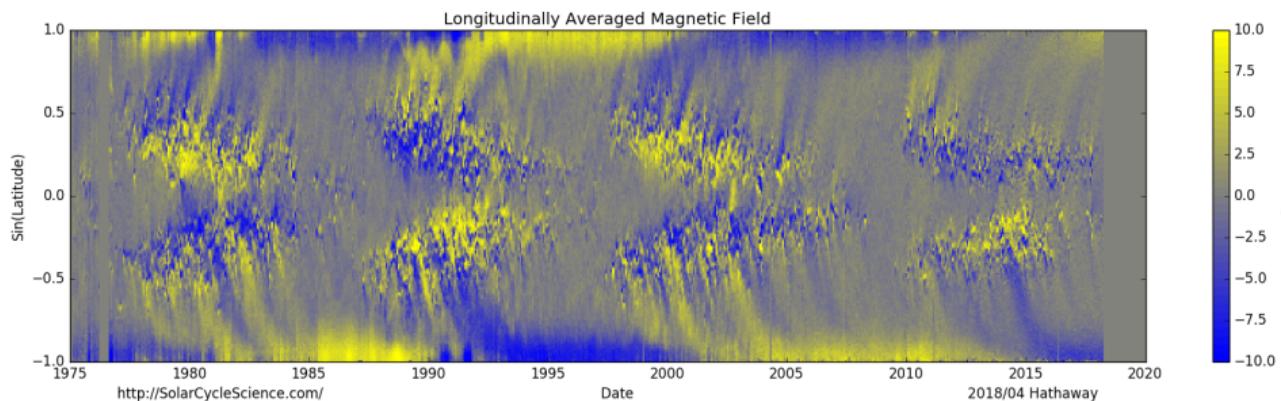
# Solar activity

Magnetic butterfly diagram

Geomagnetic impact of the solar wind

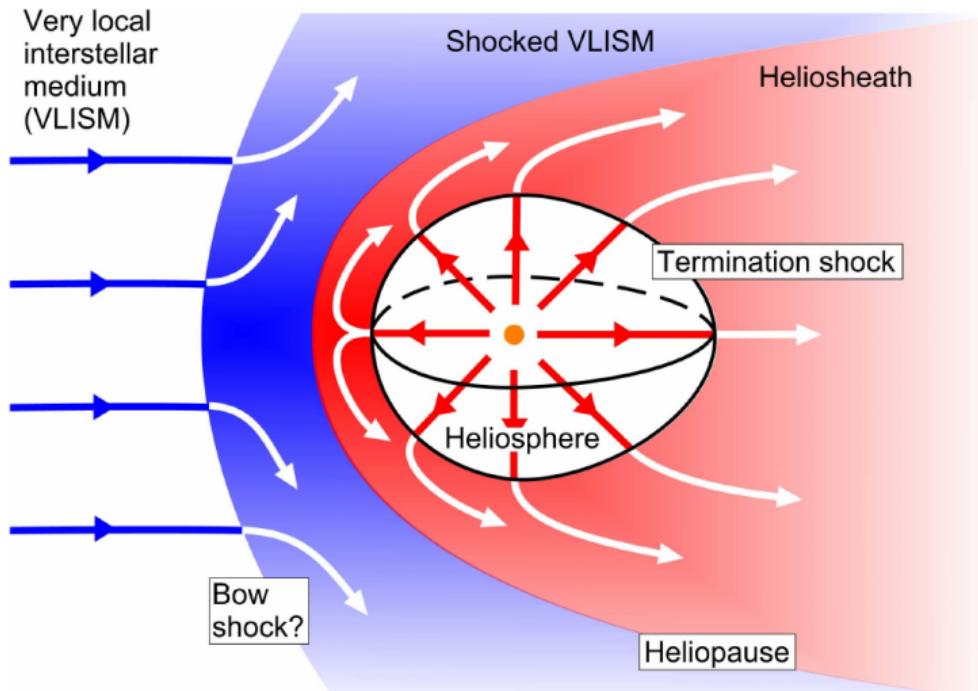


Solar wind model for the inner heliosphere



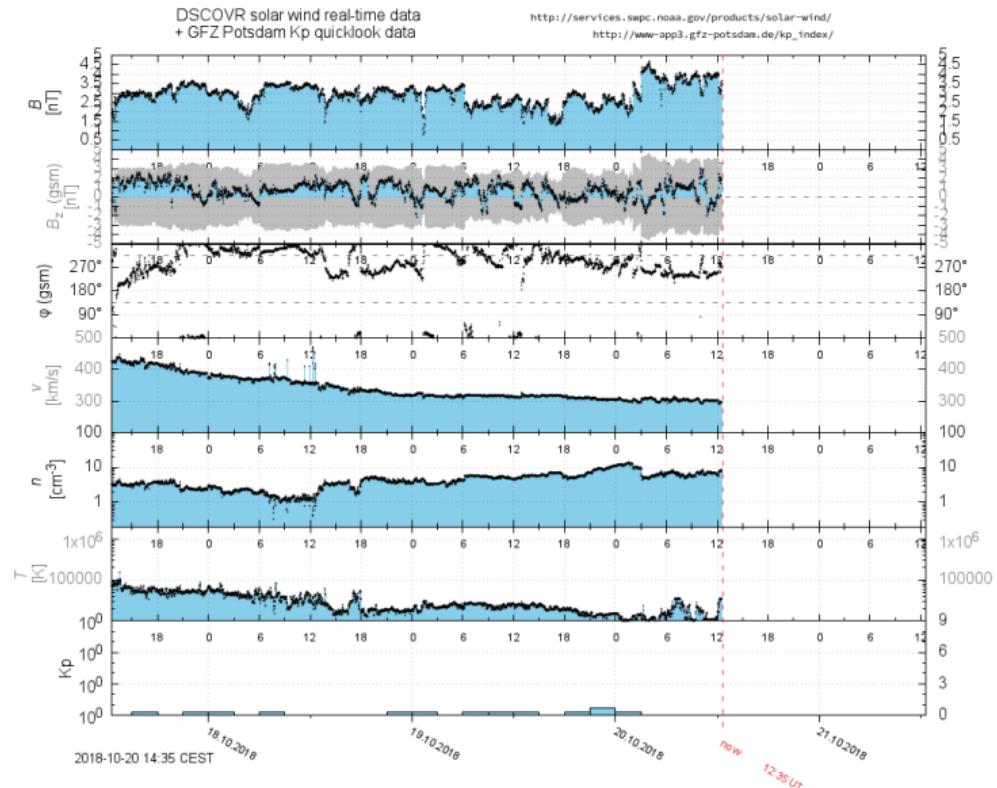
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

# Solar wind

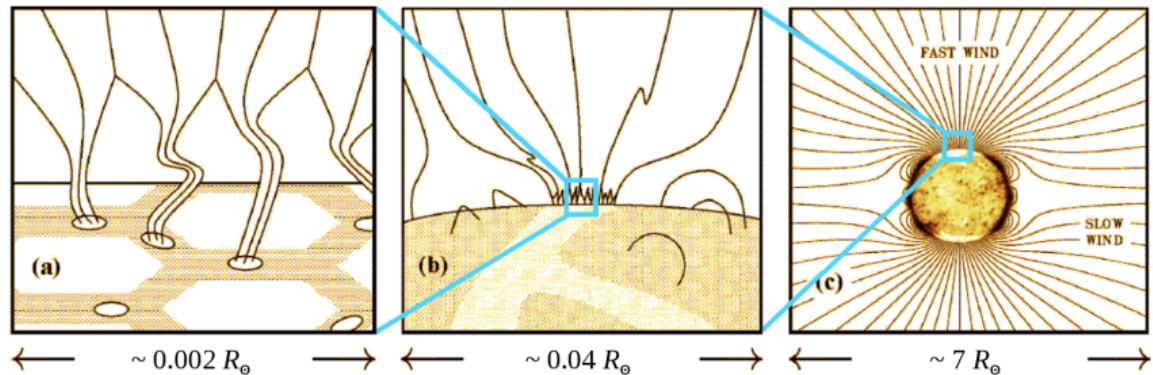


Credit: Owens & Forsyth (2013, Fig. 9)

# Solar wind

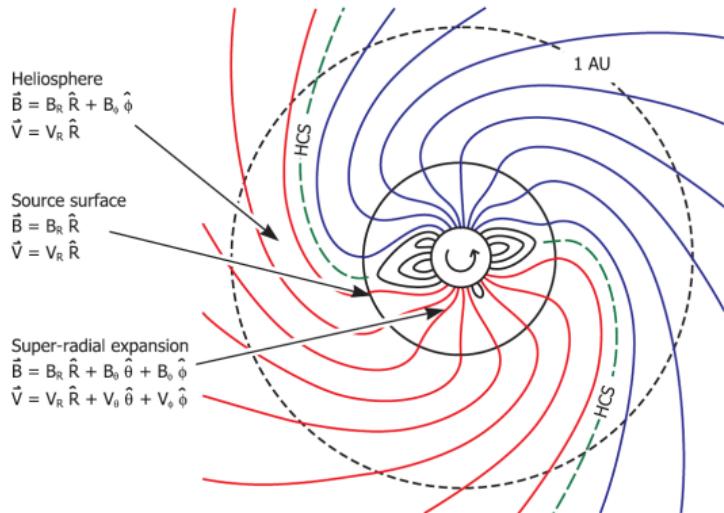


# Solar magnetic field



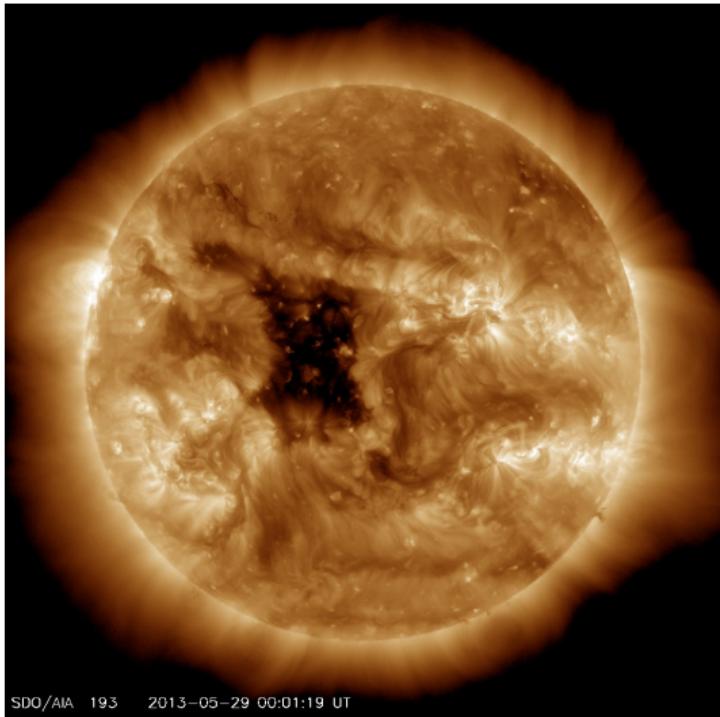
Courtesy of S. R. Cranmer

# Solar magnetic field



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

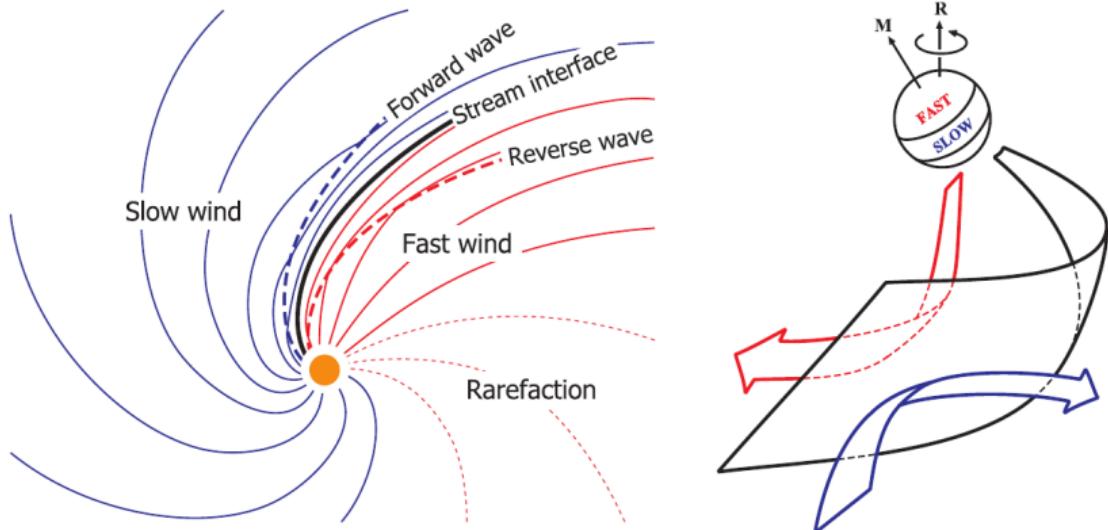
# Slow and fast solar wind



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

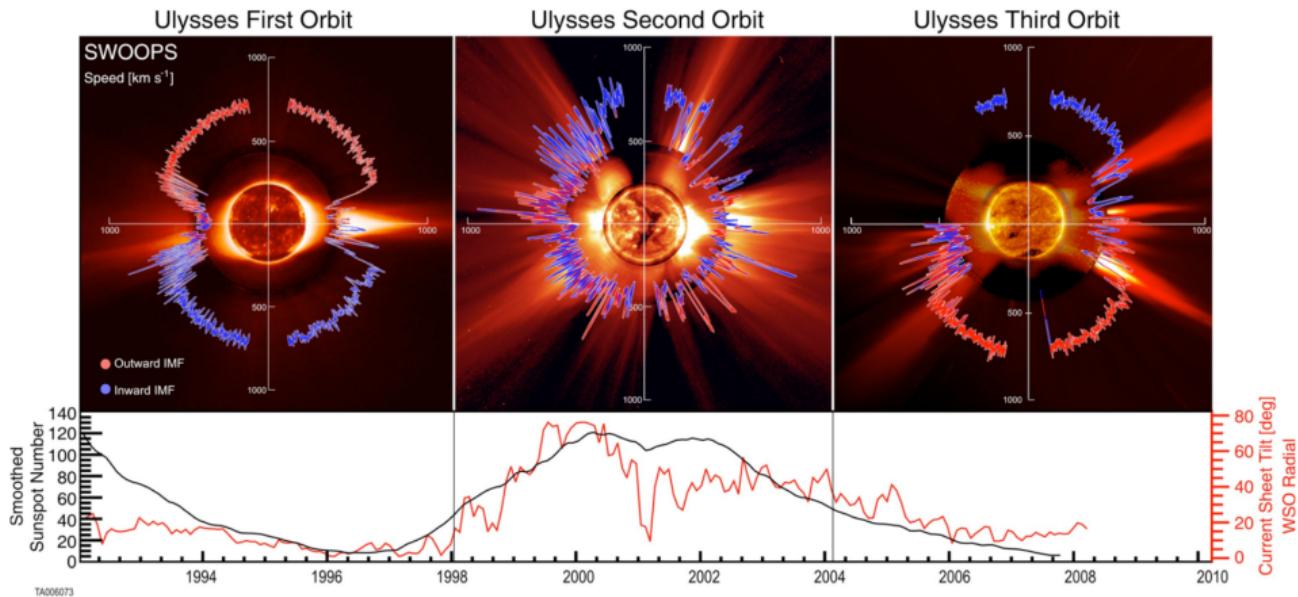


Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

# Solar activity

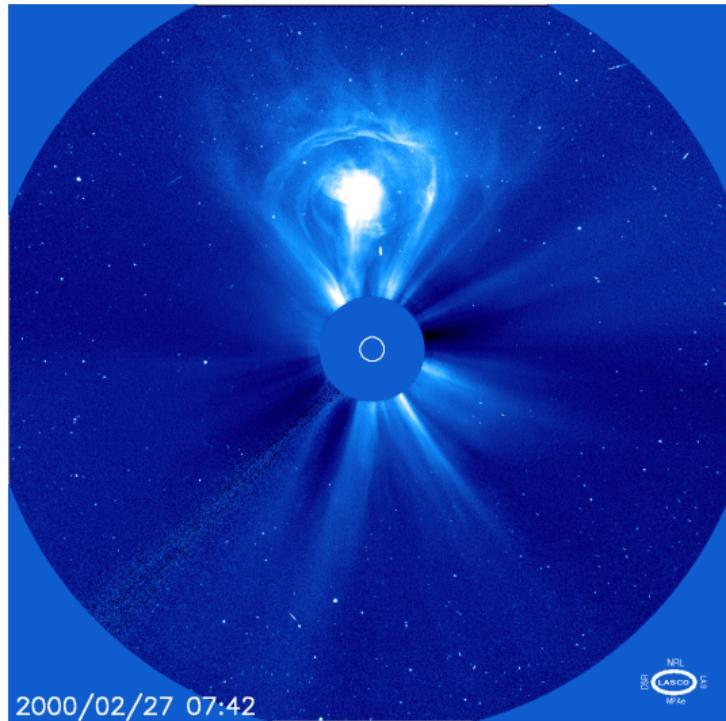
## Sunspots

# Solar activity



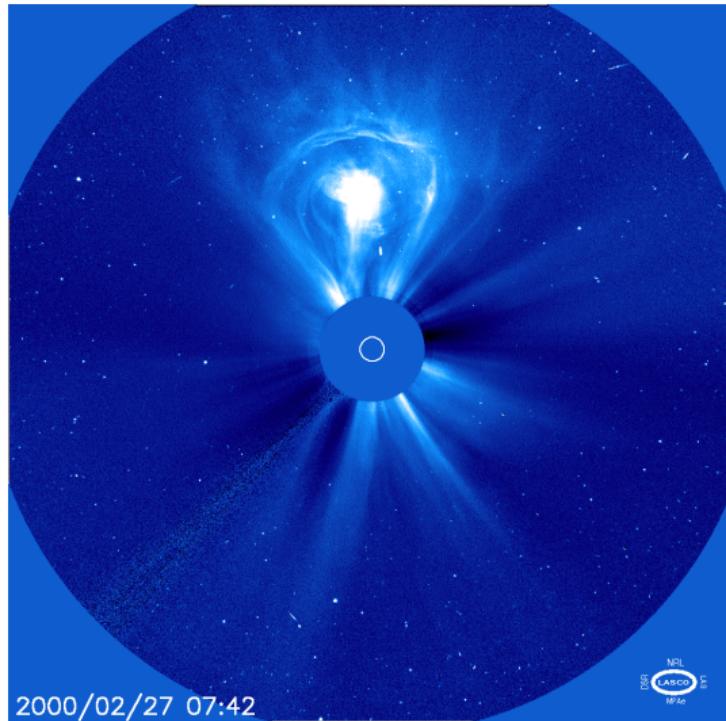
Credit: McComas et al. (2008a, Fig. 1)

# Coronal mass ejections

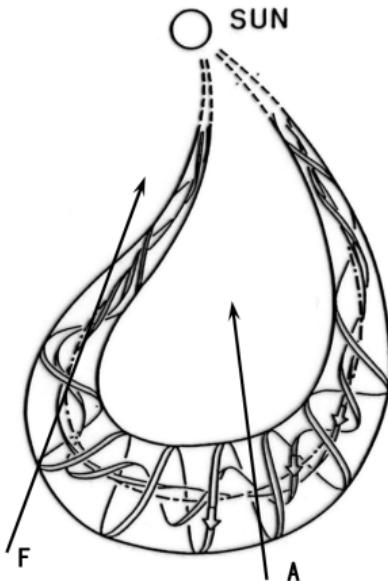


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

# Coronal mass ejections

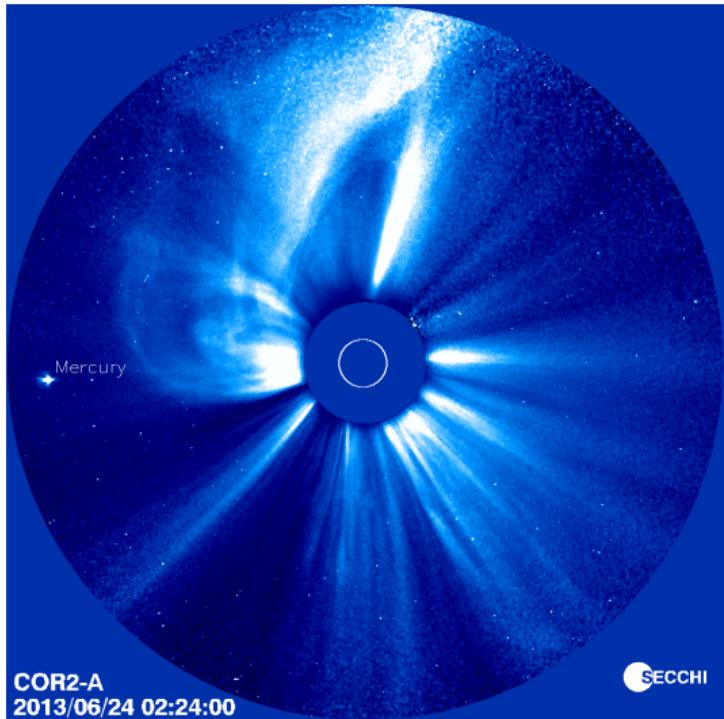


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

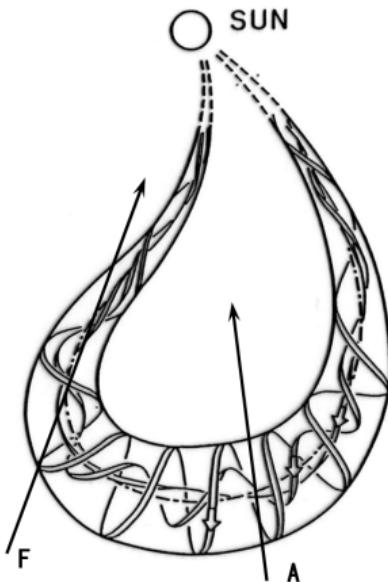


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# Coronal mass ejections

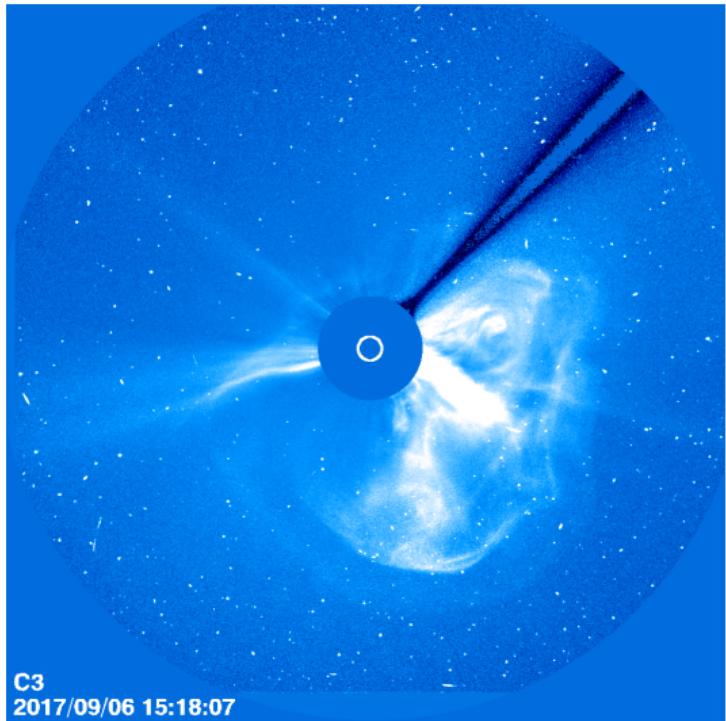


Courtesy of STEREO/COR2 consortium (NASA)



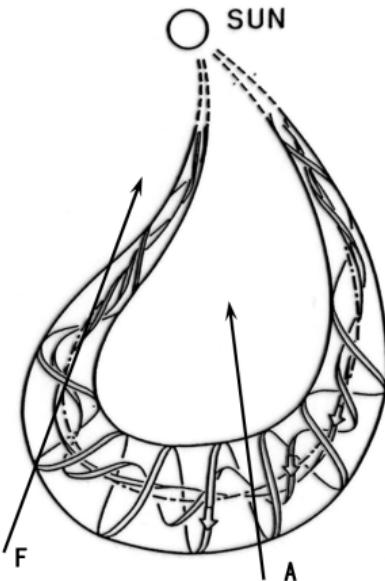
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# Coronal mass ejections



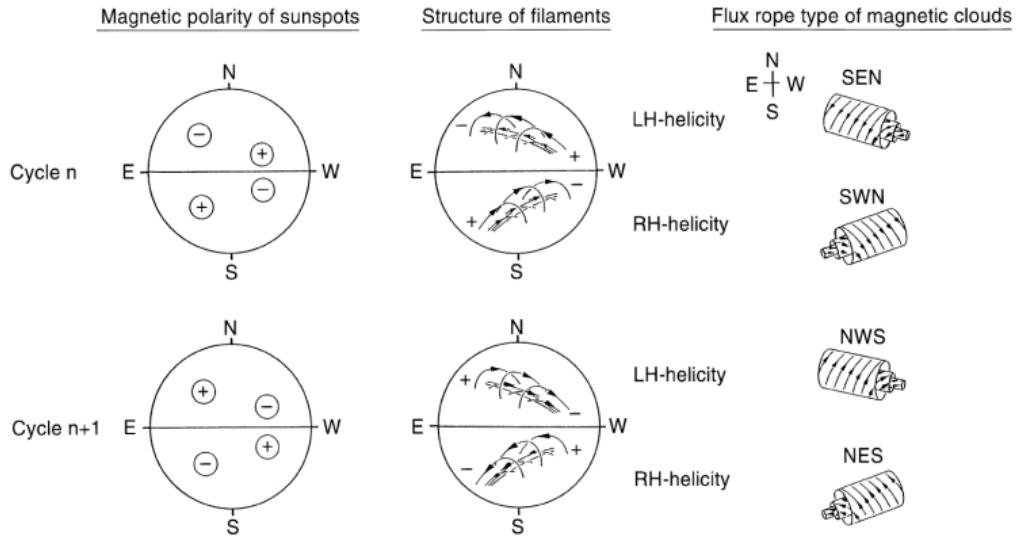
C3  
2017/09/06 15:18:07

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



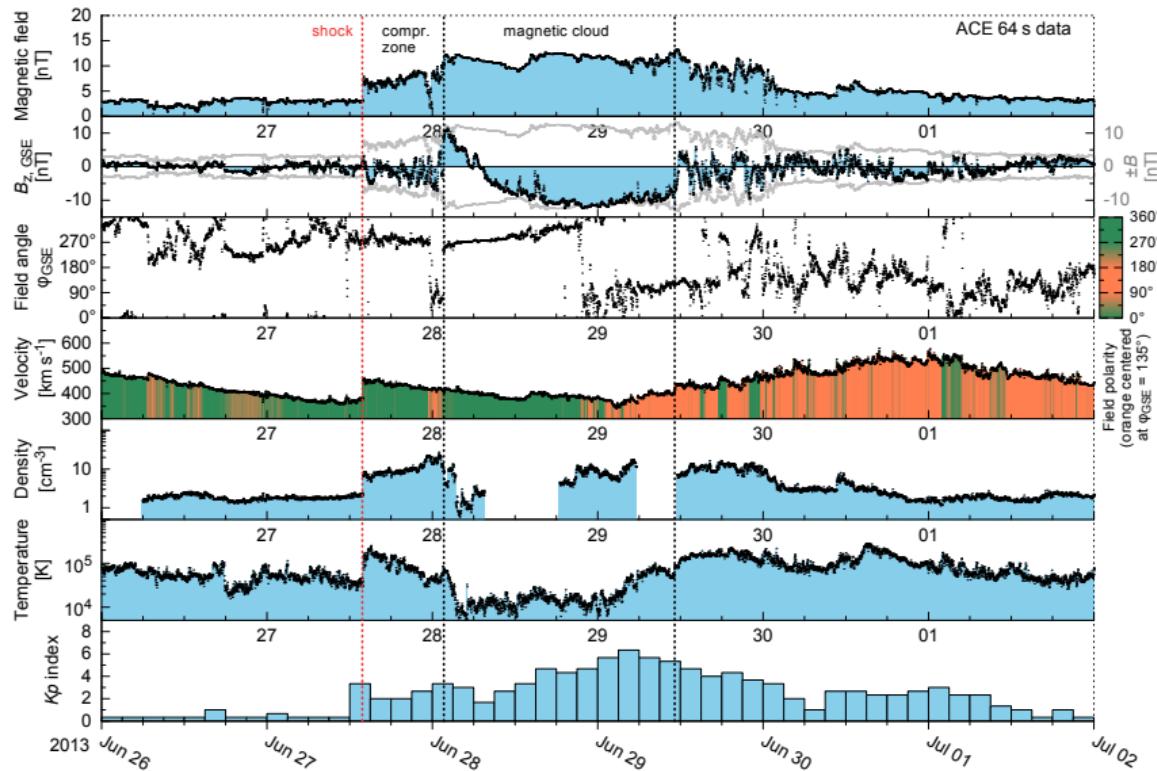
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# CME orientation

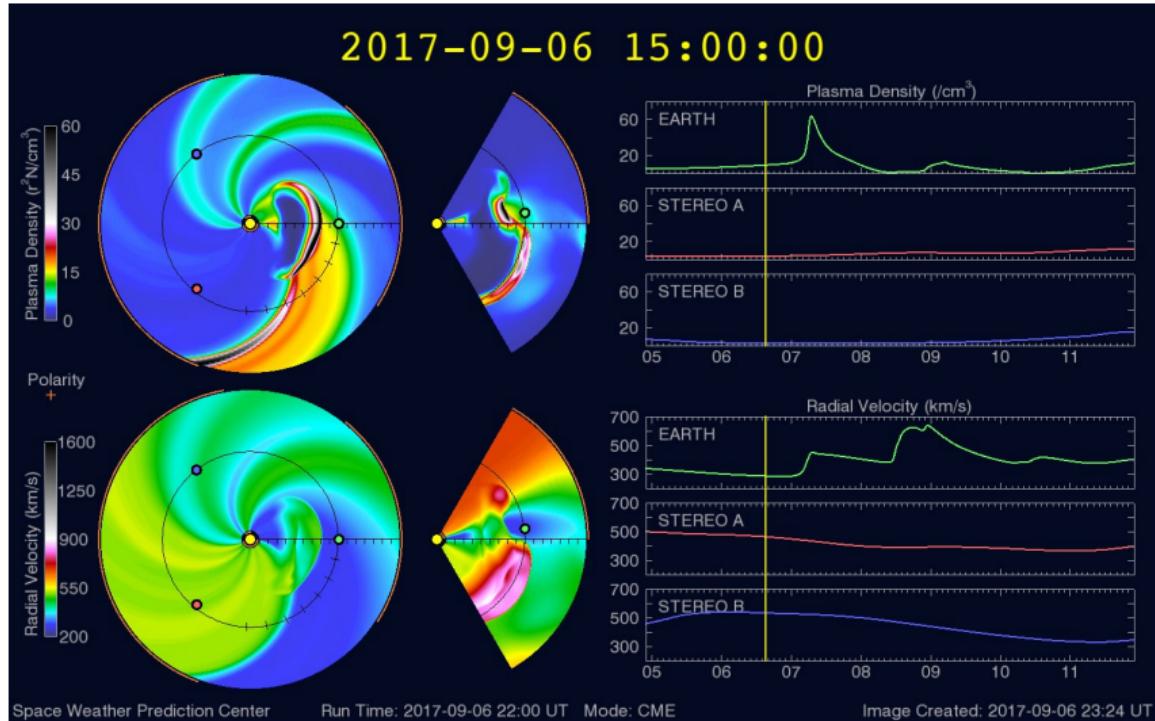


Credit: Bothmer & Schwenn (1998, Fig. 18)

# In-situ CMEs

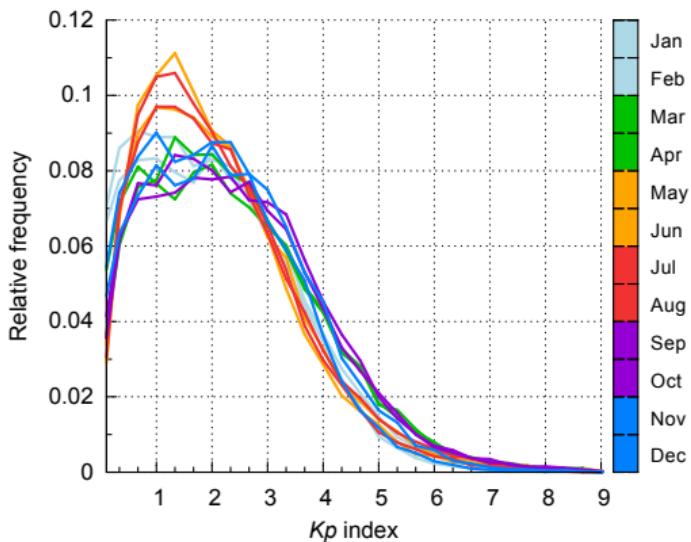
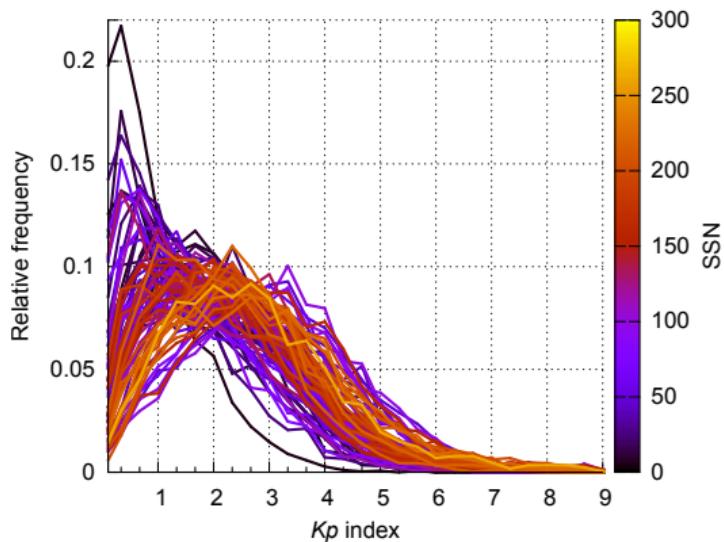


# Solar wind and CME forecast



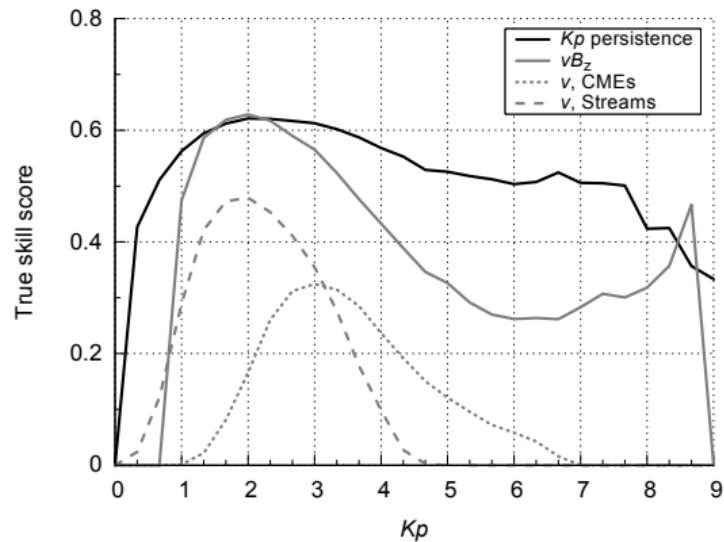
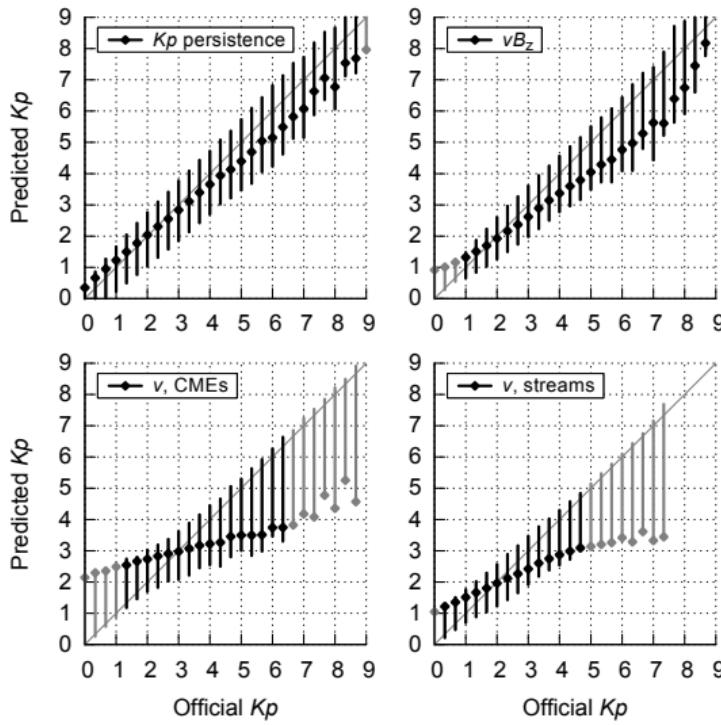
Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

## $Kp$ long-term variations



## Chapter2

## Prediction performance

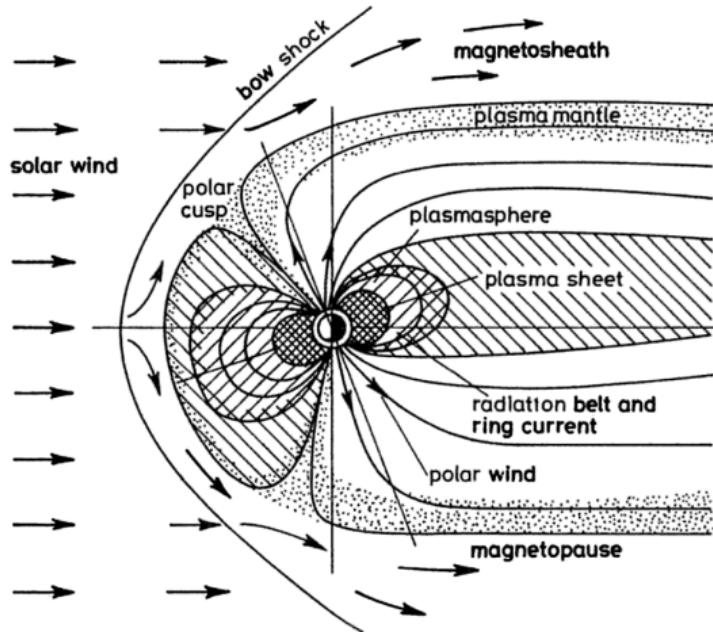


# Geomagnetic impact of the solar wind

## Aims

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

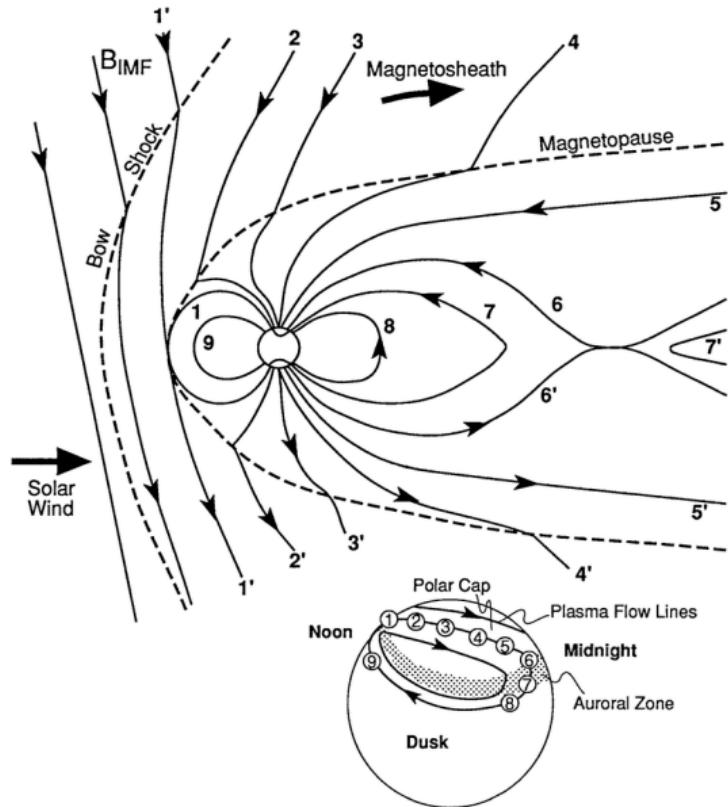
# Magnetosphere



Credit: Davies (1990, Fig. 2.12)

4 interaction mechanisms

# Magnetosphere



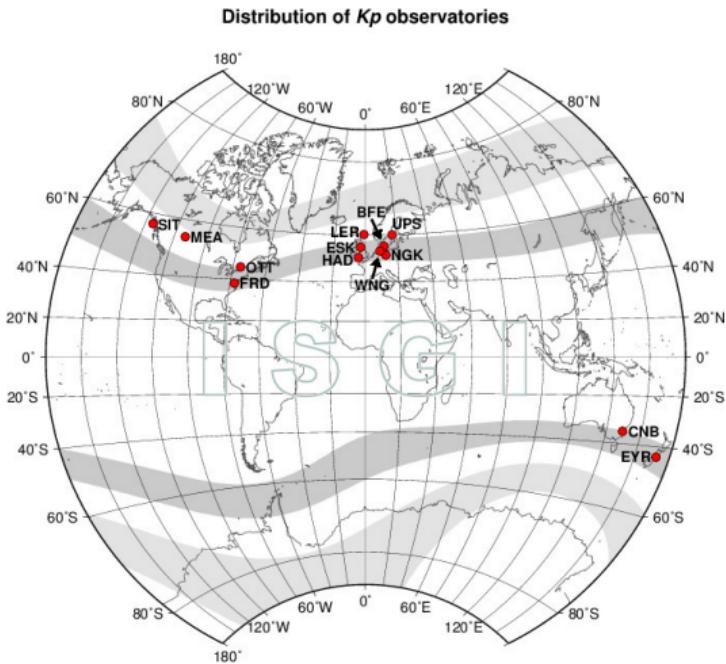
Credit: Hughes (1995, Fig. 9.11)

# Magnetosphere

4 factors for merging flux rate

# *Kp* index

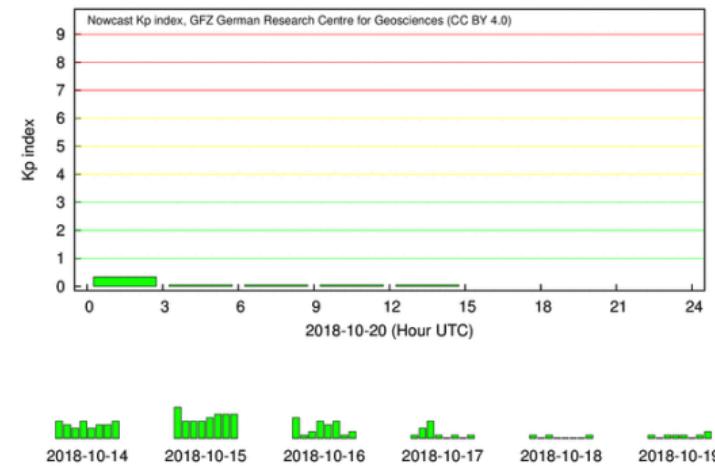
13 observatories...



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

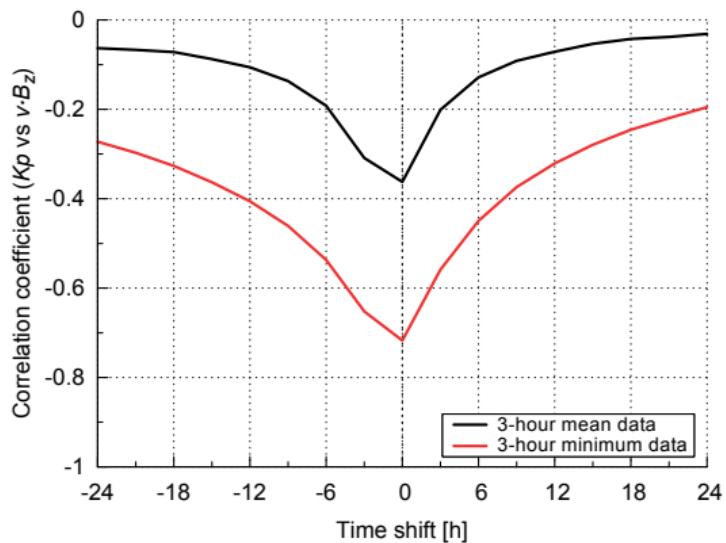
# *Kp* index

## Quicklook *Kp*

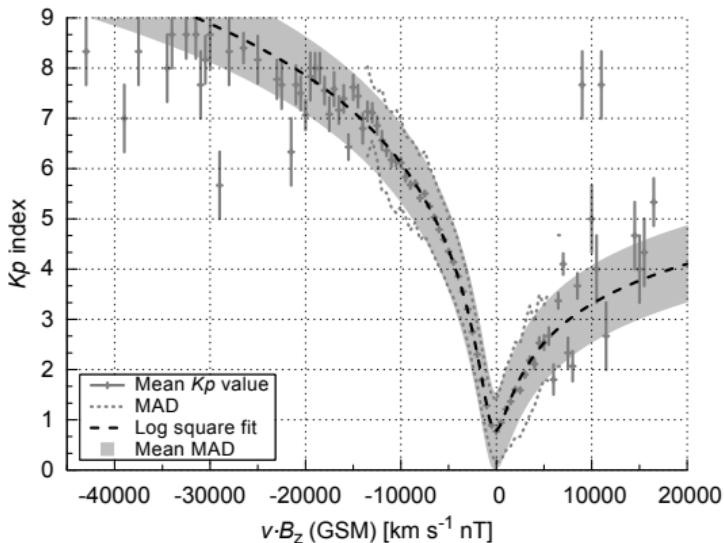
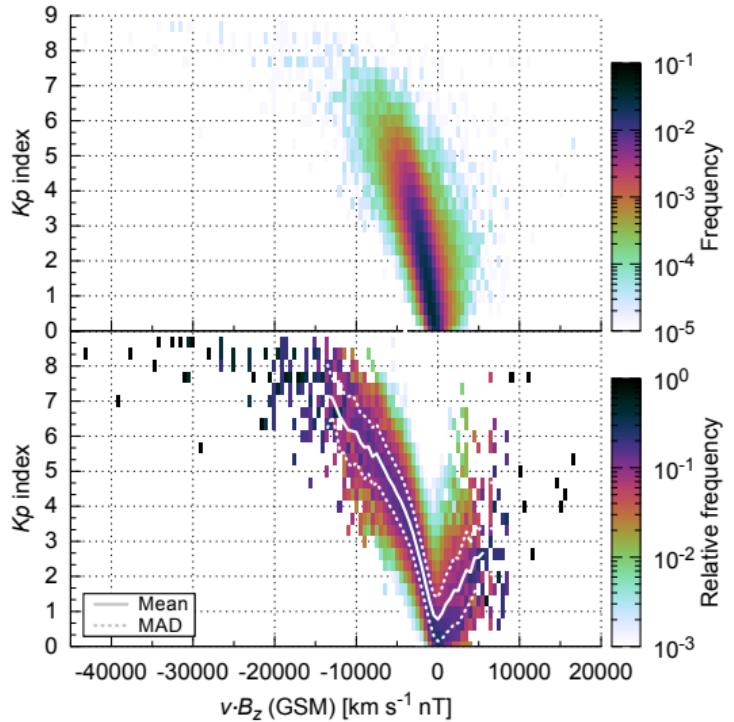


Credit: GFZ Potsdam, 2018

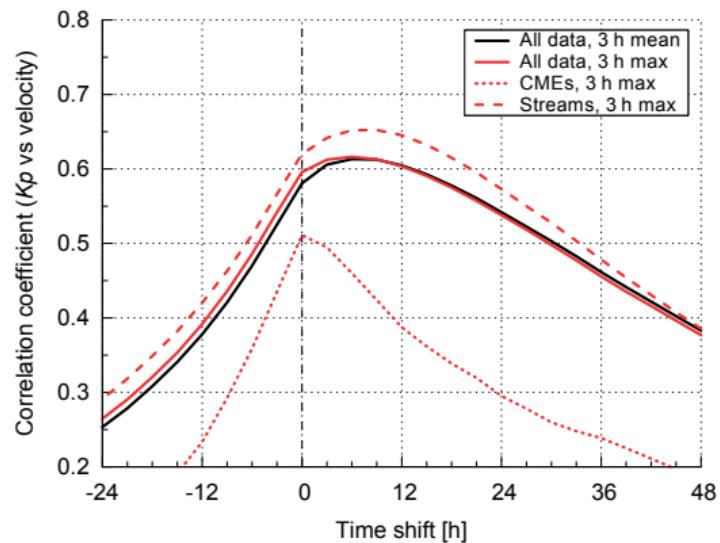
## Solar wind electric field



# Solar wind electric field



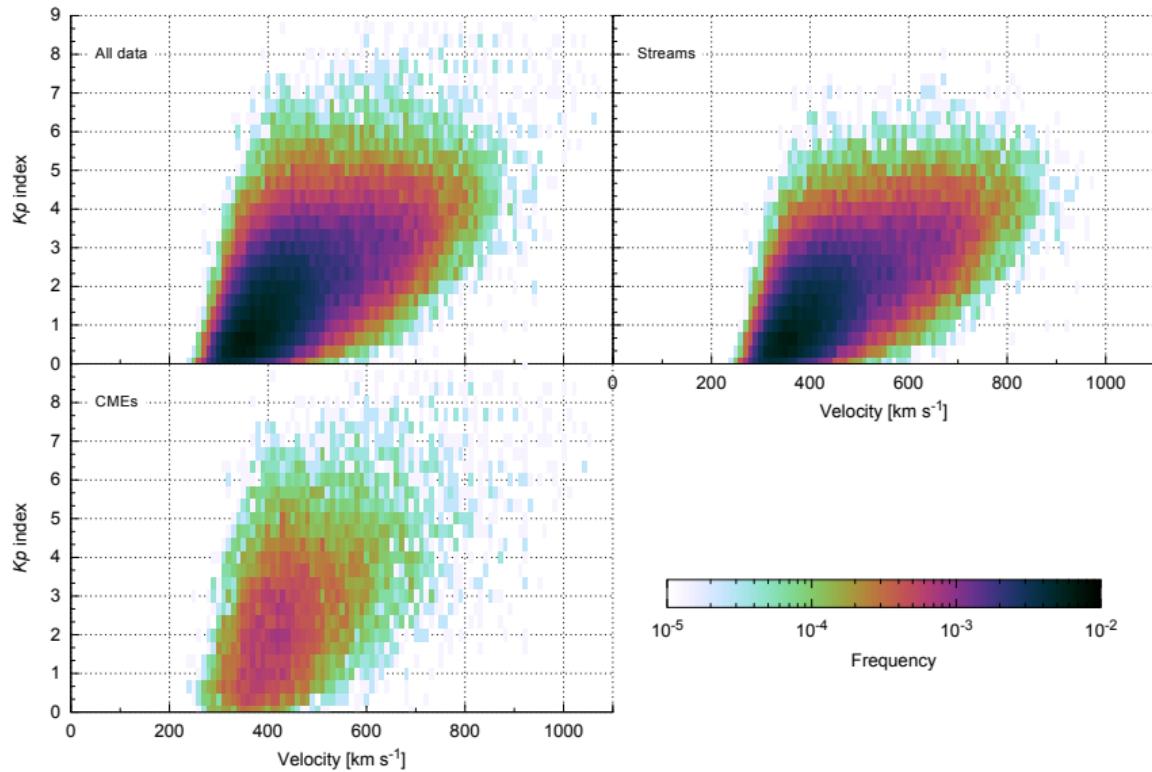
# Solar wind velocity

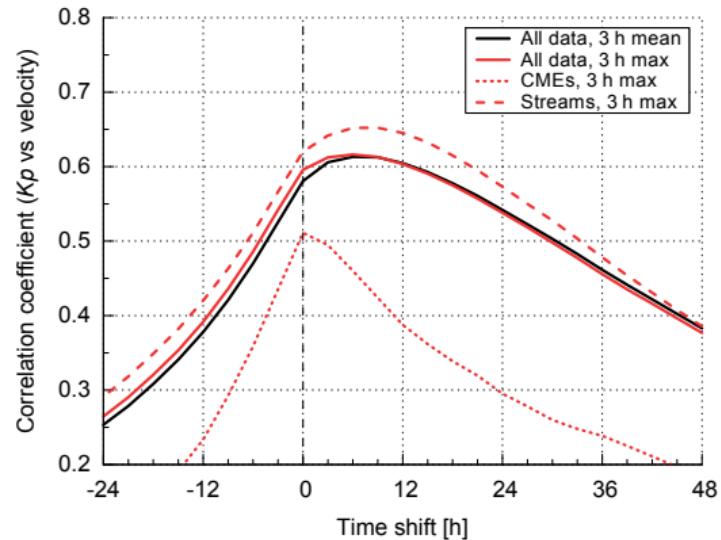


## Solar wind velocity

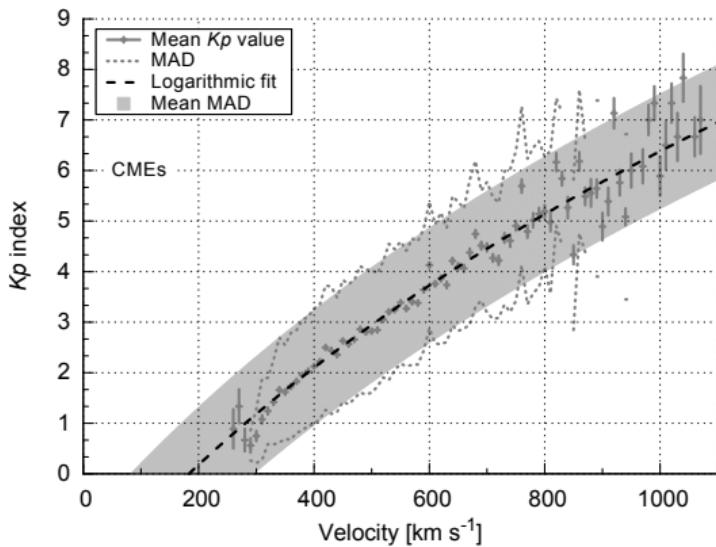
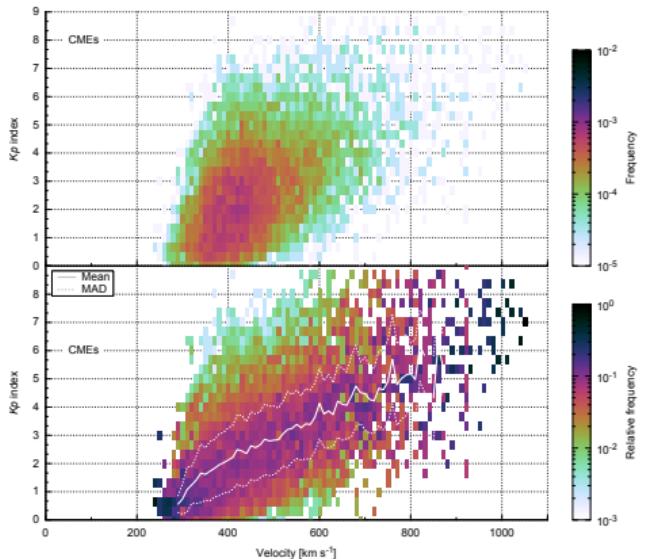
CME – stream separation  
Solar Wind Structures list

# Solar wind velocity

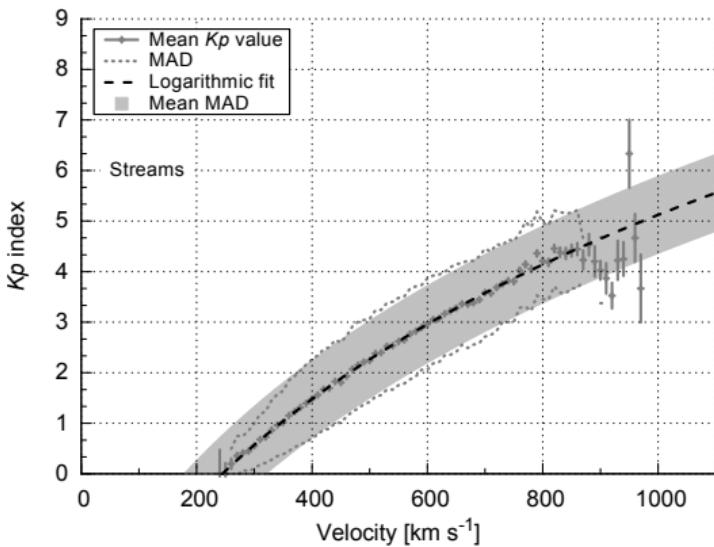
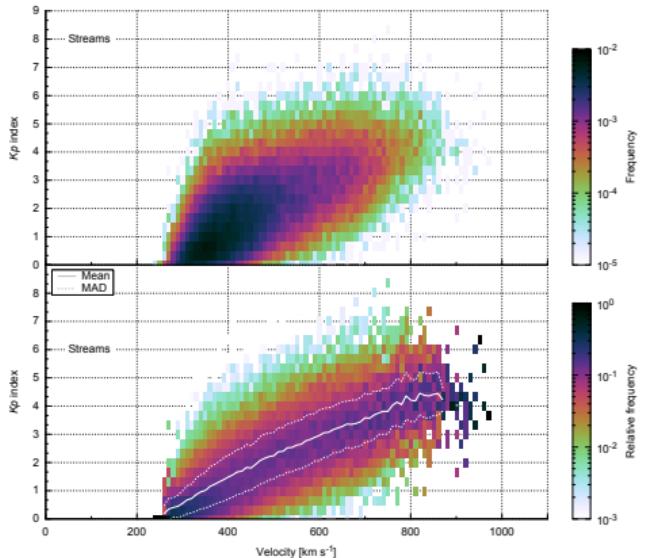


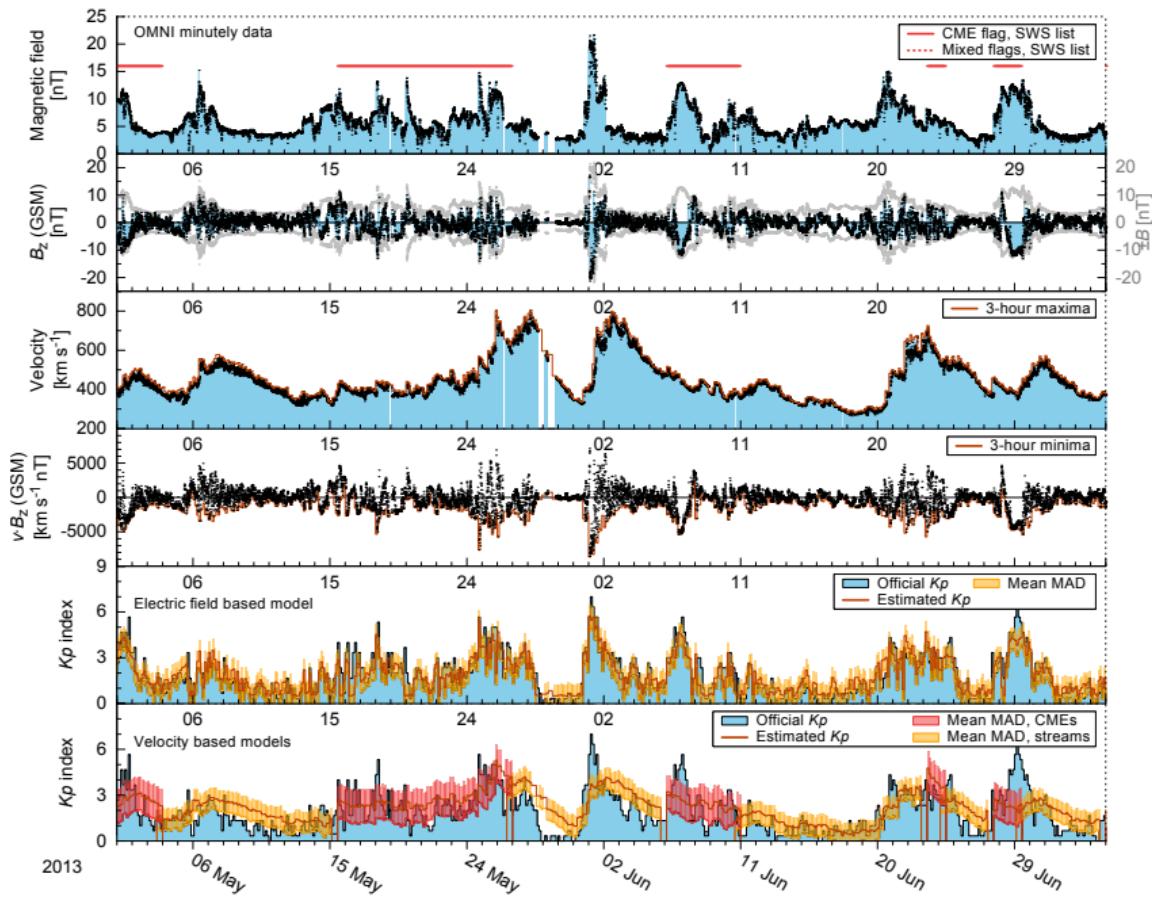


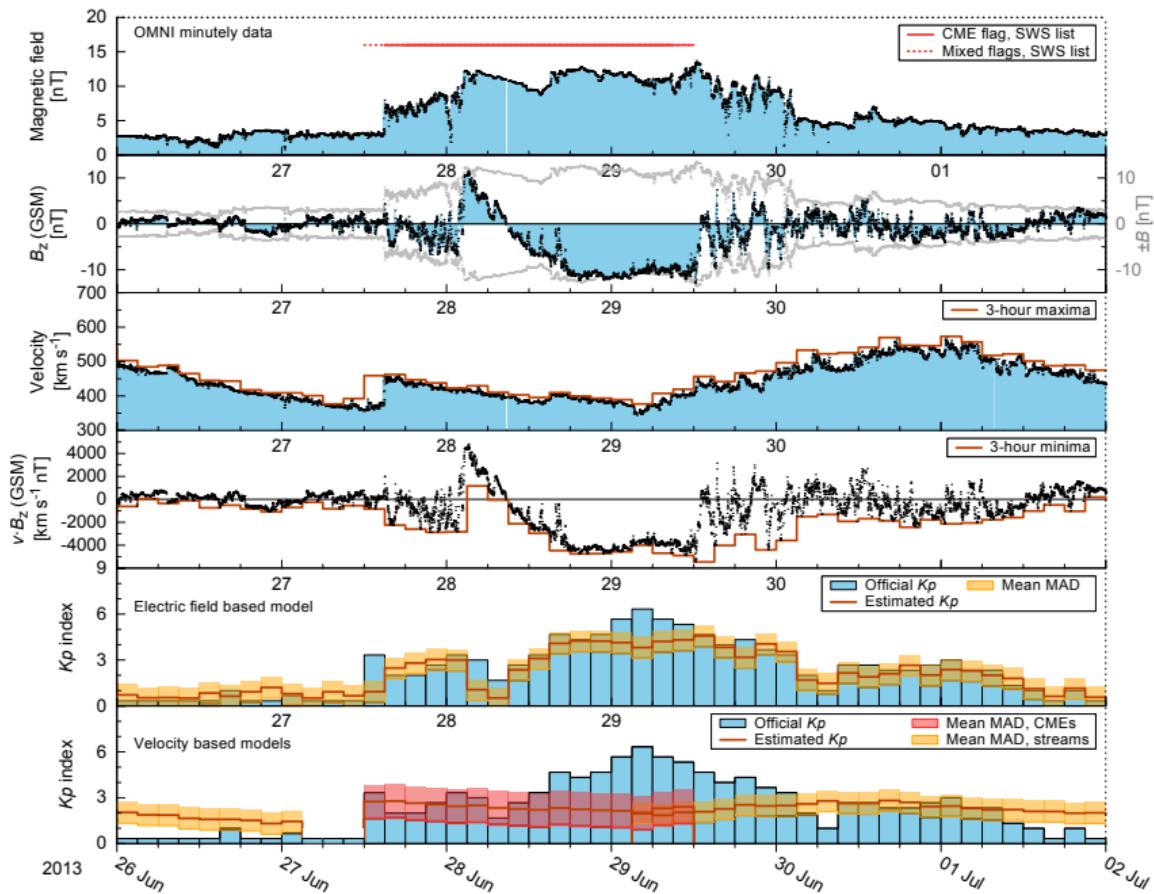
# CME velocity



# Stream velocity







## Results

Predictive  $K_p$  models based on relations with

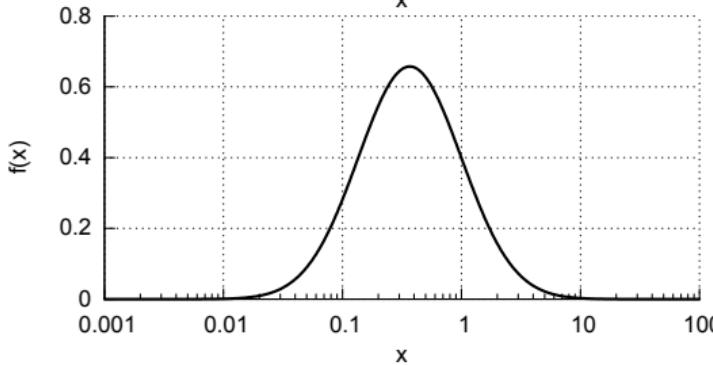
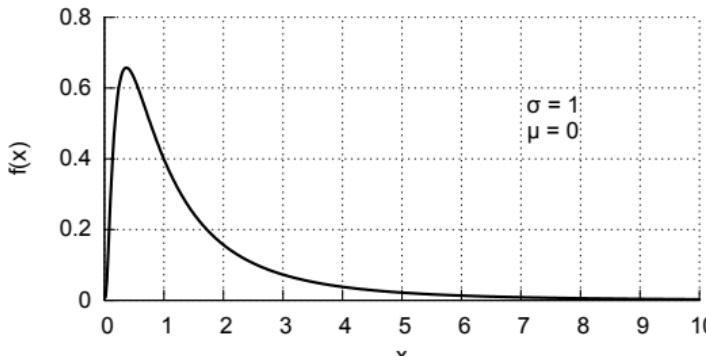
- solar wind electric field proxy ( $vB_z$ )
- velocity of CME-associated flows ( $v_{\text{CME}}$ )
- velocity of solar wind streams ( $v_{\text{stream}}$ )

## 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 ( $\sigma$ )

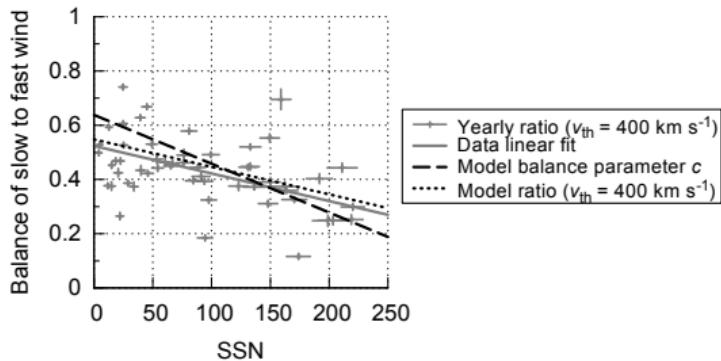
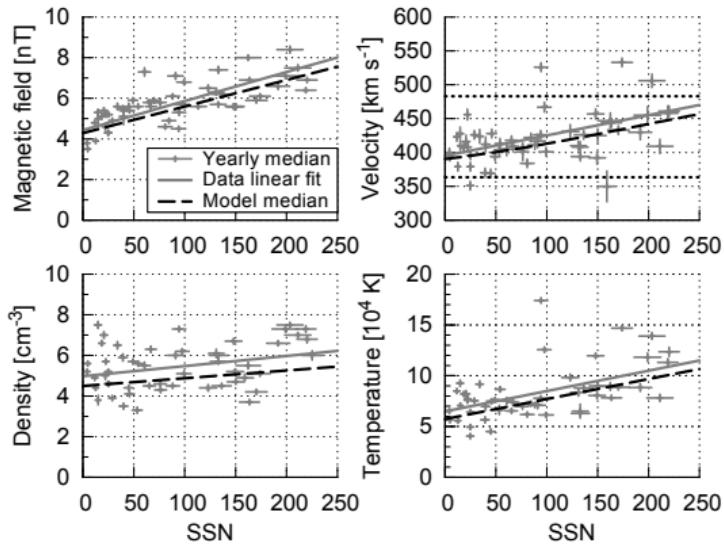
## Sun–Earth evolution of the solar wind

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

combine models, extrapolation

# PSP perihelia prediction

