

# 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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Seminarraum Astrophysik (SR 17, F 05.104)

## Contents

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

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

# Contents

## 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

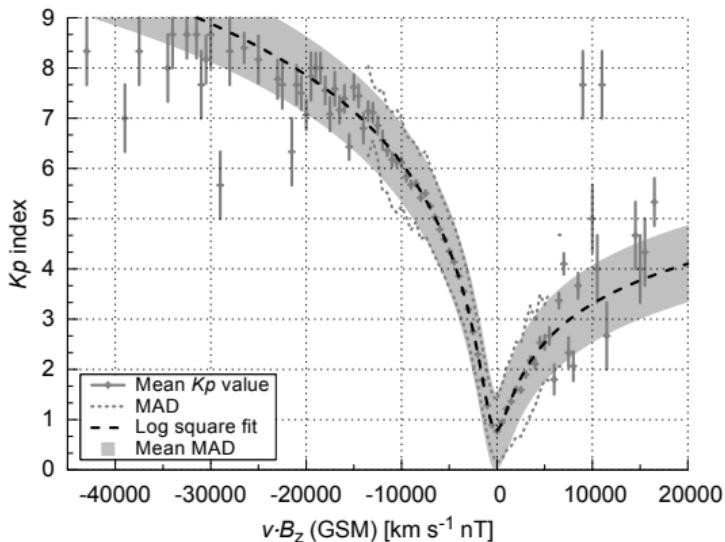
## Geomagnetic impact of the solar wind

- $K_p$  index
- Coupling mechanisms
- Reconnection at magnetopause

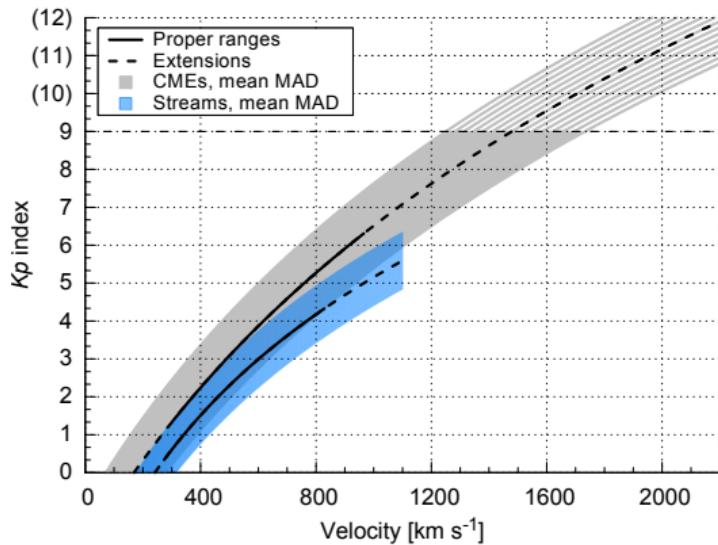
# Geomagnetic impact of the solar wind

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

Electric field proxy ( $vB_z$ )



Velocity of CMEs and streams

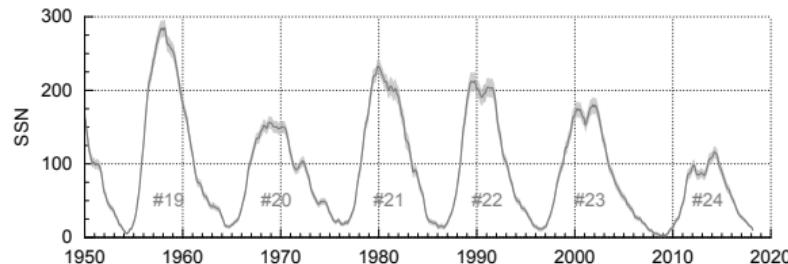


## Solar wind

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

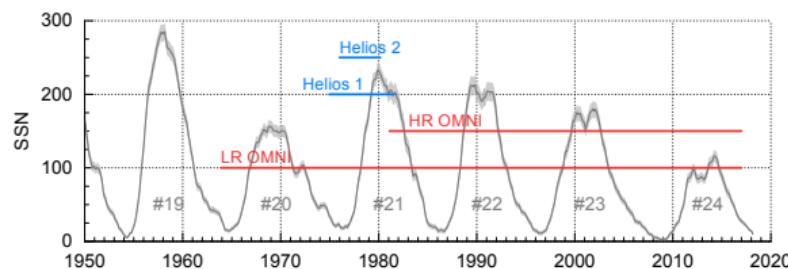
# Solar wind

- E. Parker's theoretical model
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# Solar wind

- E. Parker's theoretical model
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Measured in-situ throughout the heliosphere:

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

# Solar wind



Total Solar Eclipse 2017

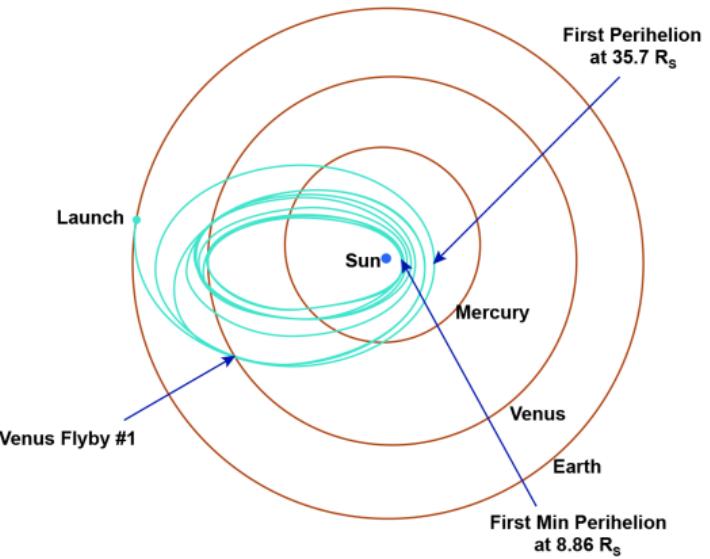
© 2017 Miloslav Druckmüller, Zuzana Druckmüllerová, Jana Hoderová, Petr Štarha, Shadia Habbal

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

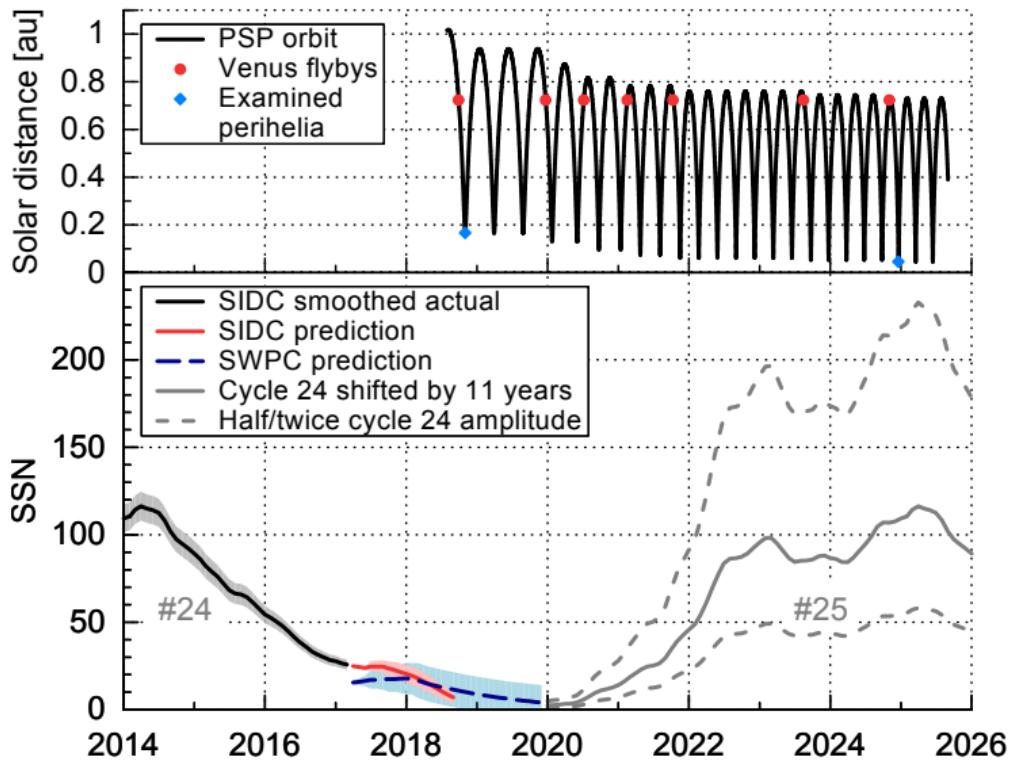
### Solar wind key parameters

- Magnetic field strength
- Velocity
- Density
- Temperature

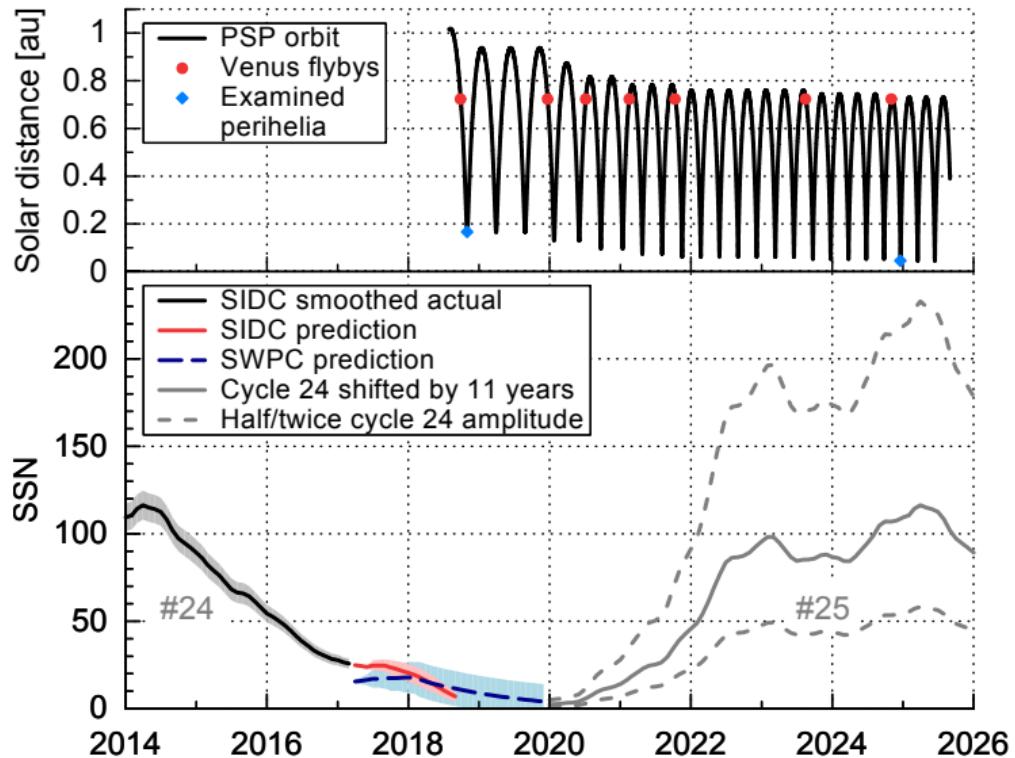
values shifted according to solar activity and solar distance

unique: frequency distributions

# PSP distance and SSN prediction



# PSP distance and SSN prediction

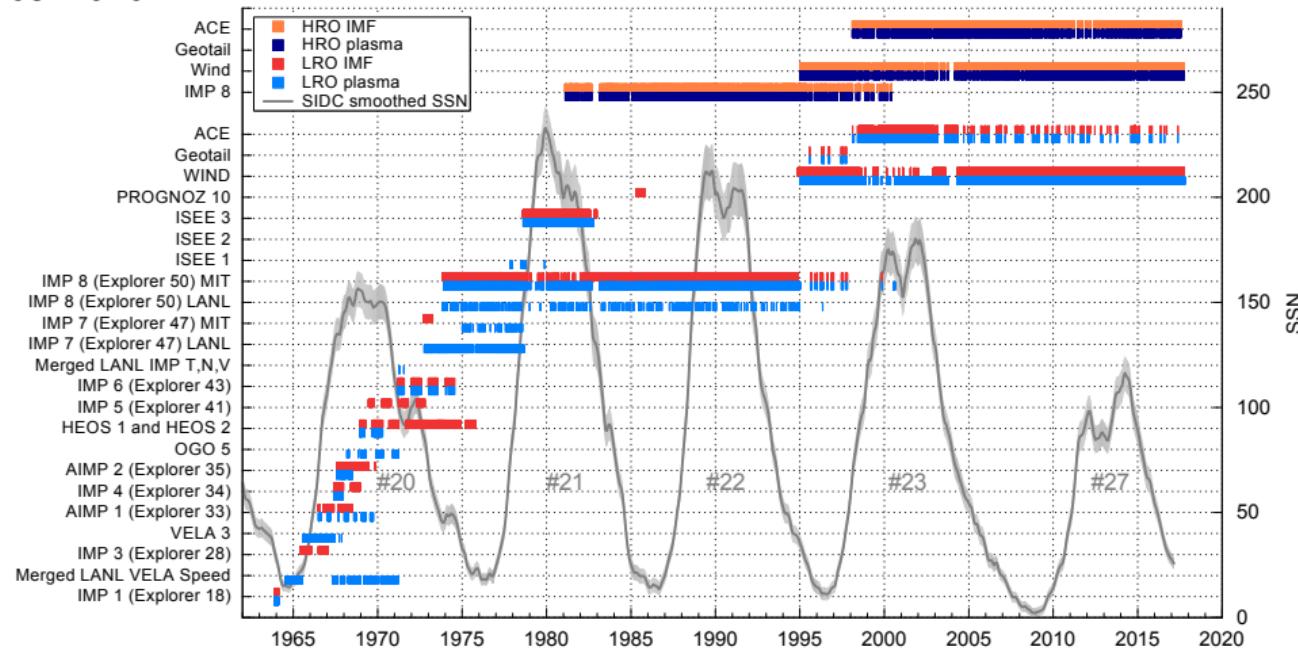


2018: solar minimum  
2024: solar maximum

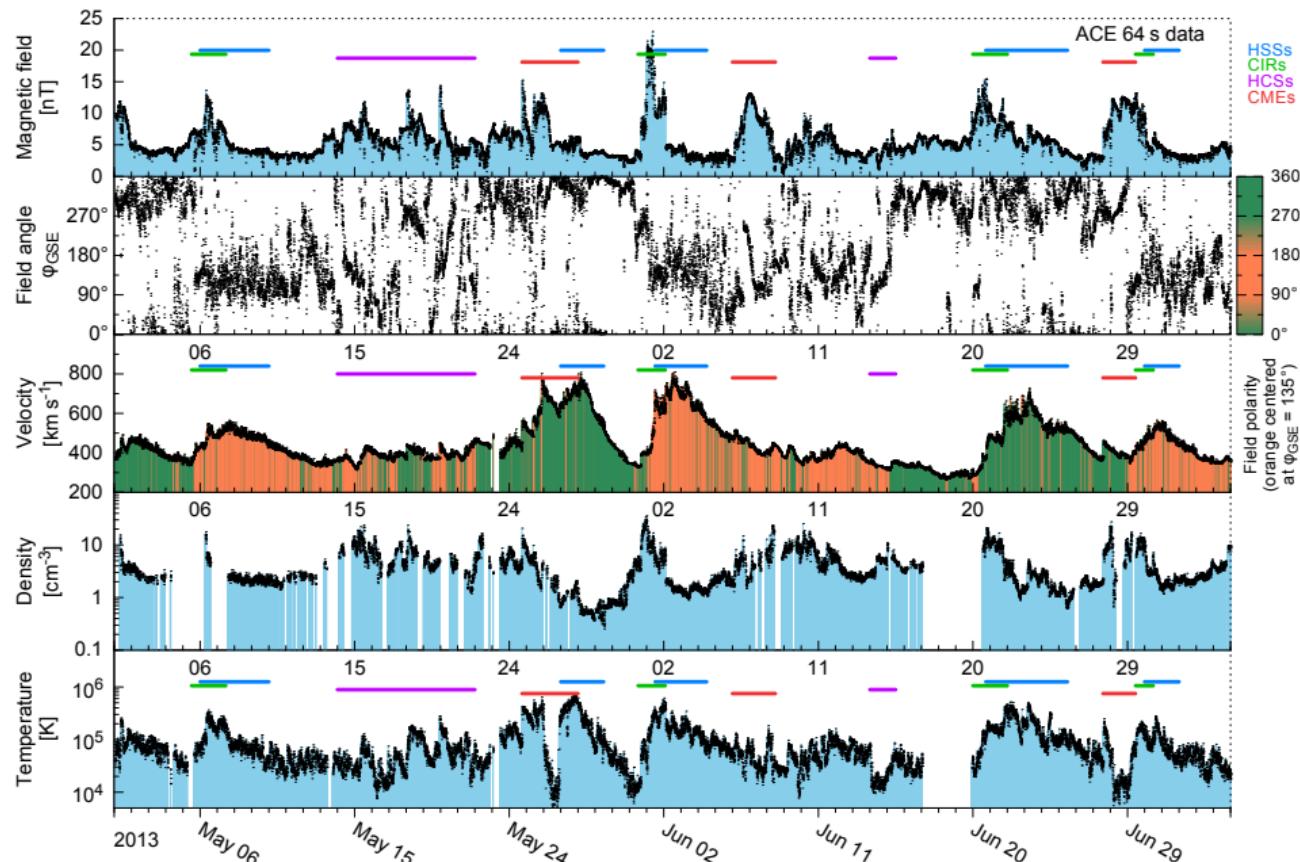
# OMNI data set

OMNI data set (King & Papitashvili, 2005)

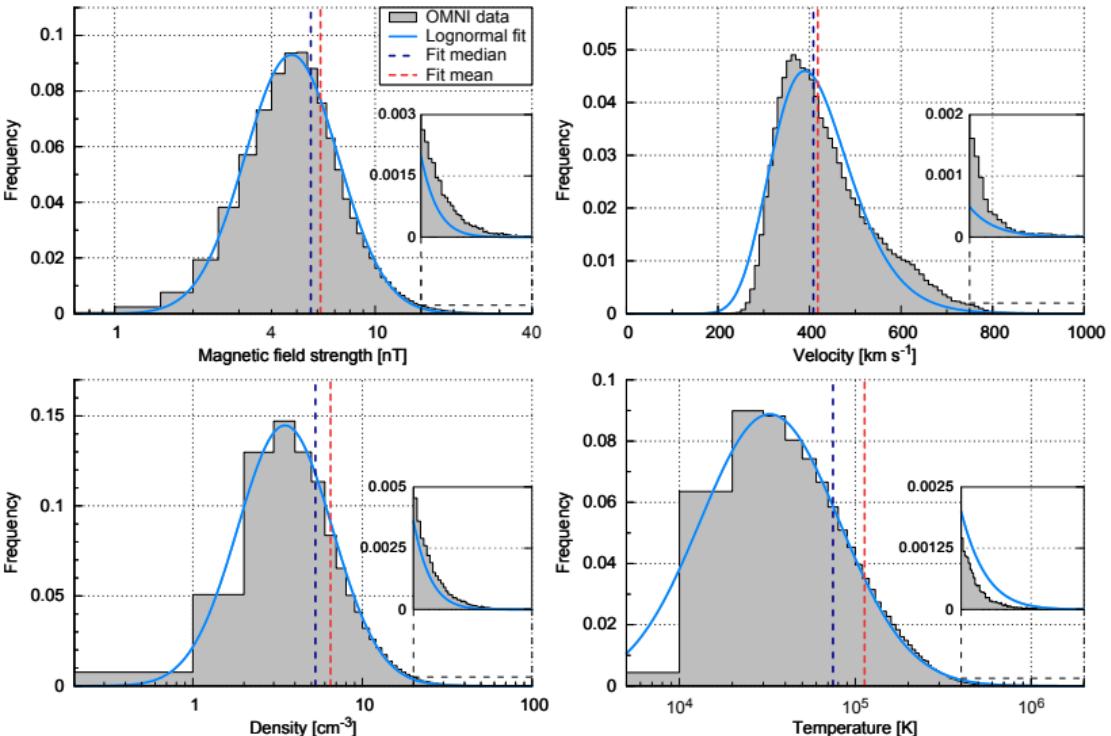
- intercalibrated multi-spacecraft data
- time-shifted to the bow shock of the magnetosphere
- 1963–2016



# OMNI data set

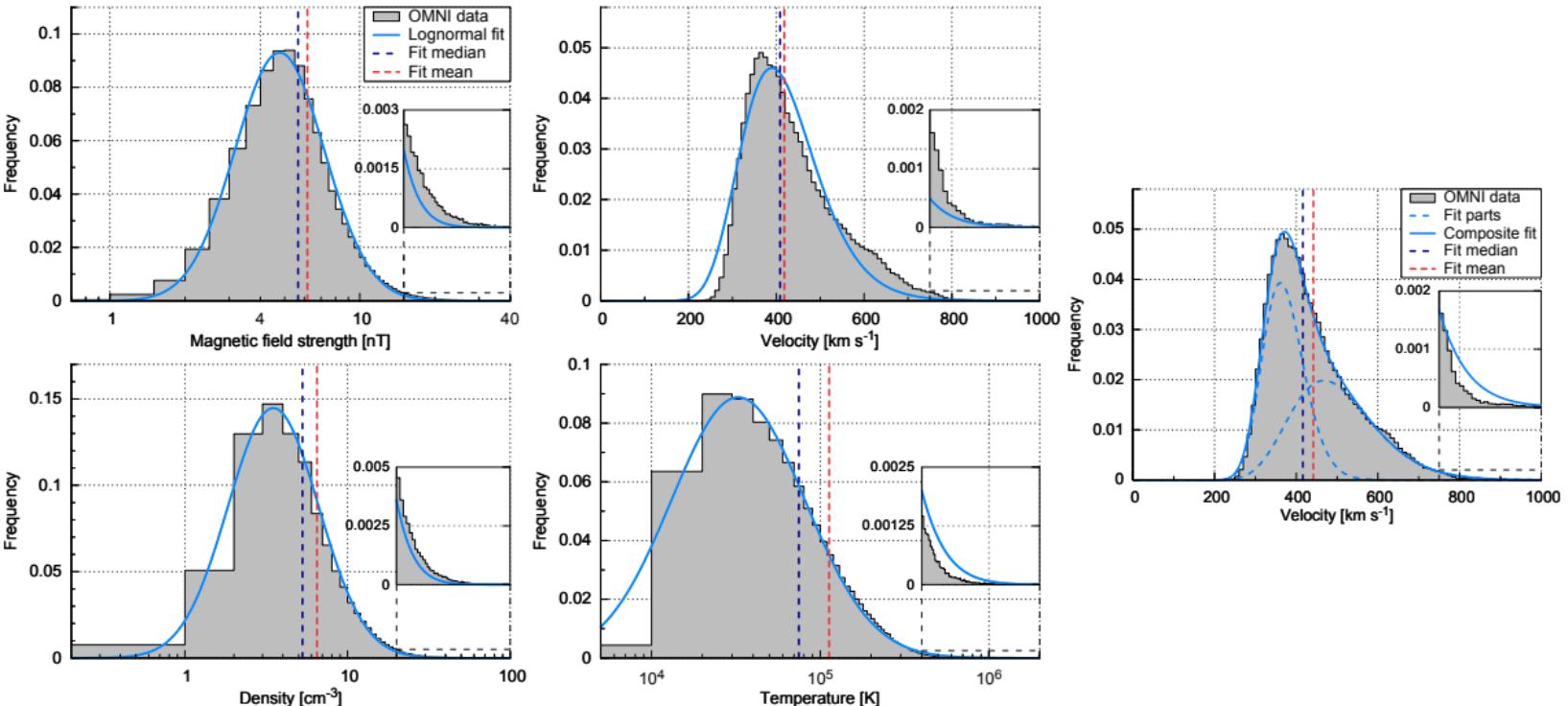


# Frequency distributions



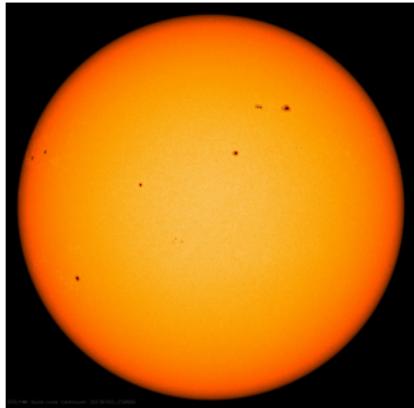
» Lognormal distribution

# Frequency distributions

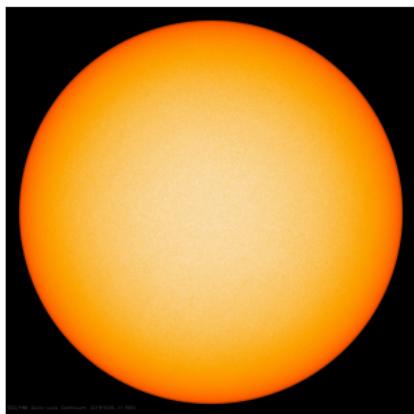


» Lognormal distribution

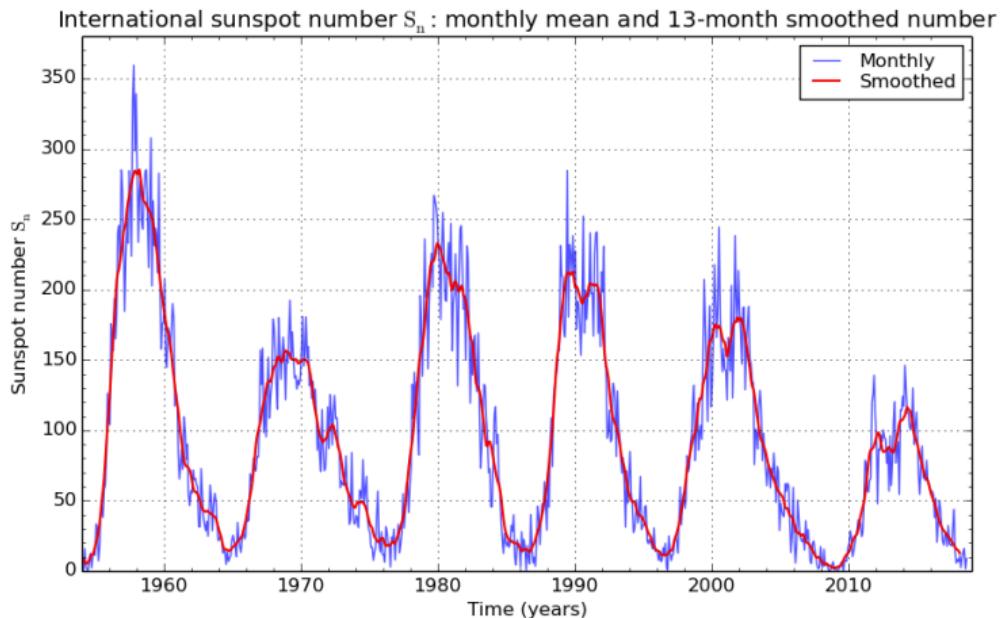
# Solar activity



Credit: NASA SDO/HMI, 1 January 2013



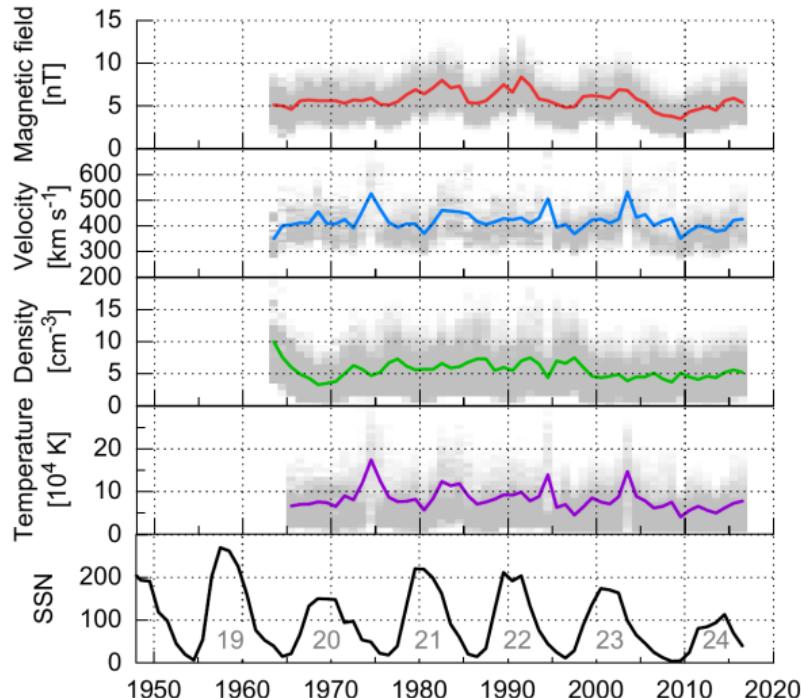
Credit: NASA SDO/HMI, 26 October 2018



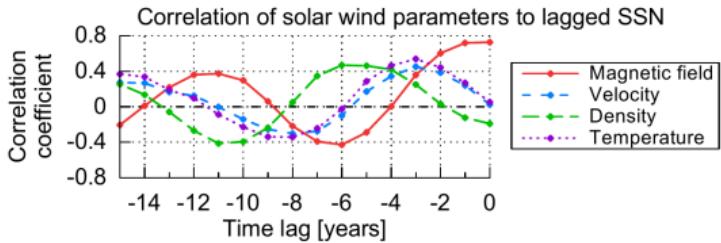
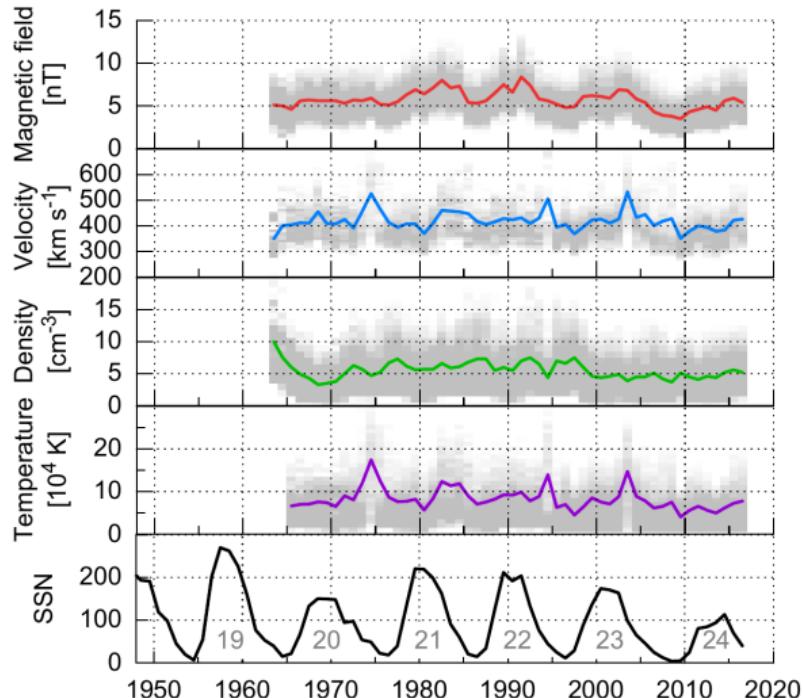
SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2018 September 1

» Magnetic butterfly diagram

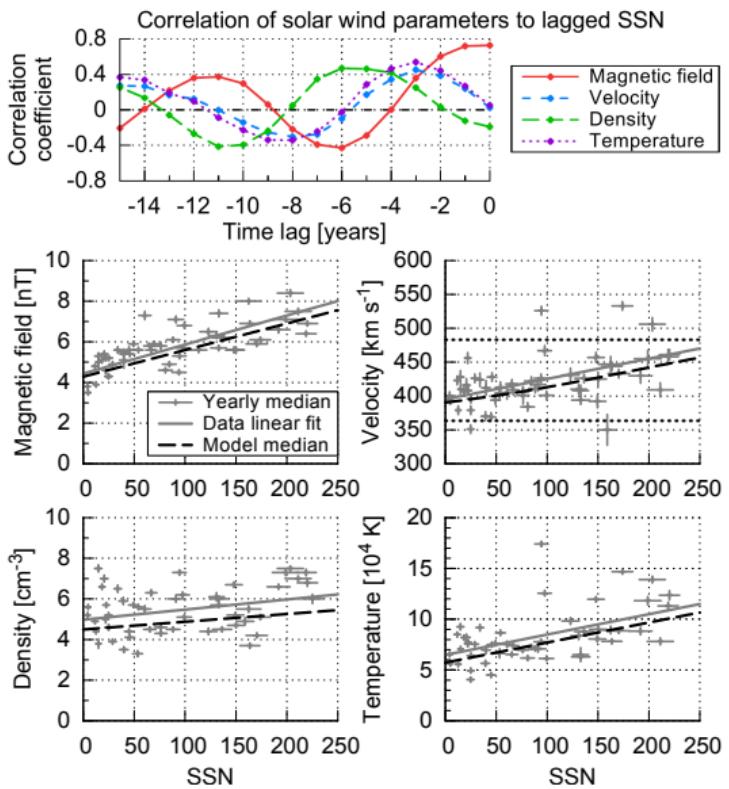
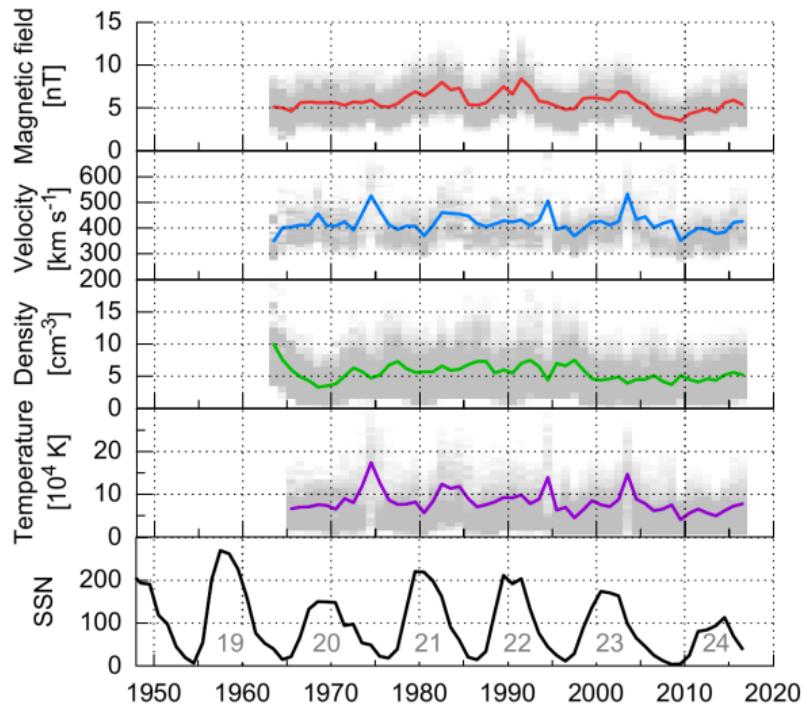
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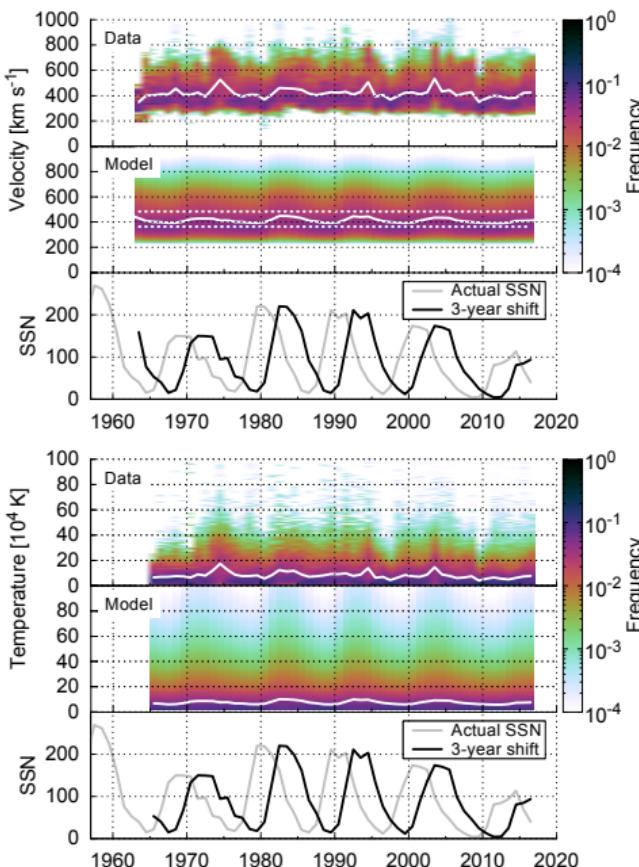
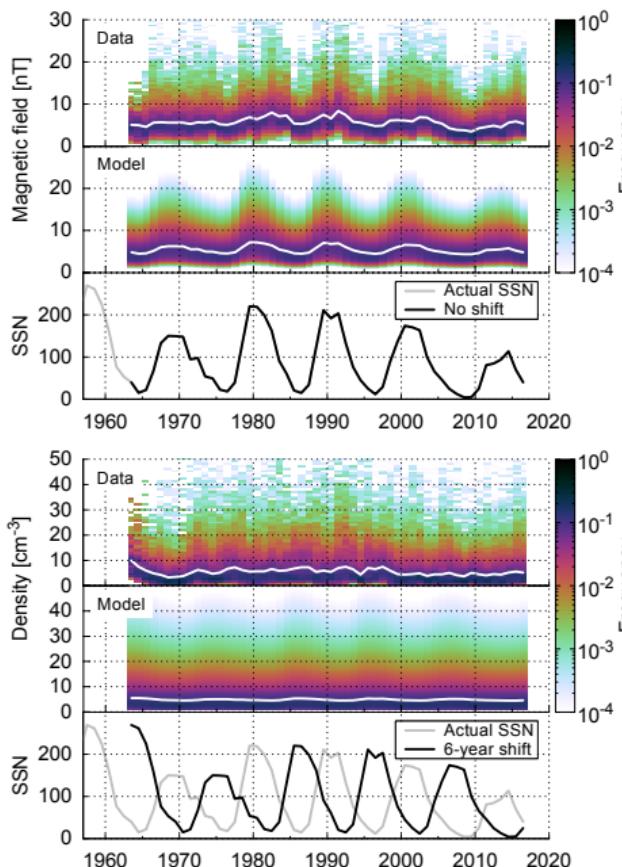
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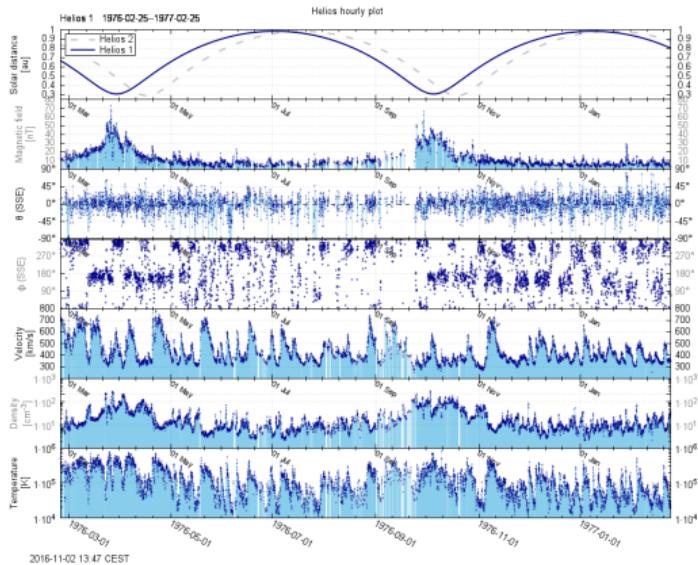


# Helios data

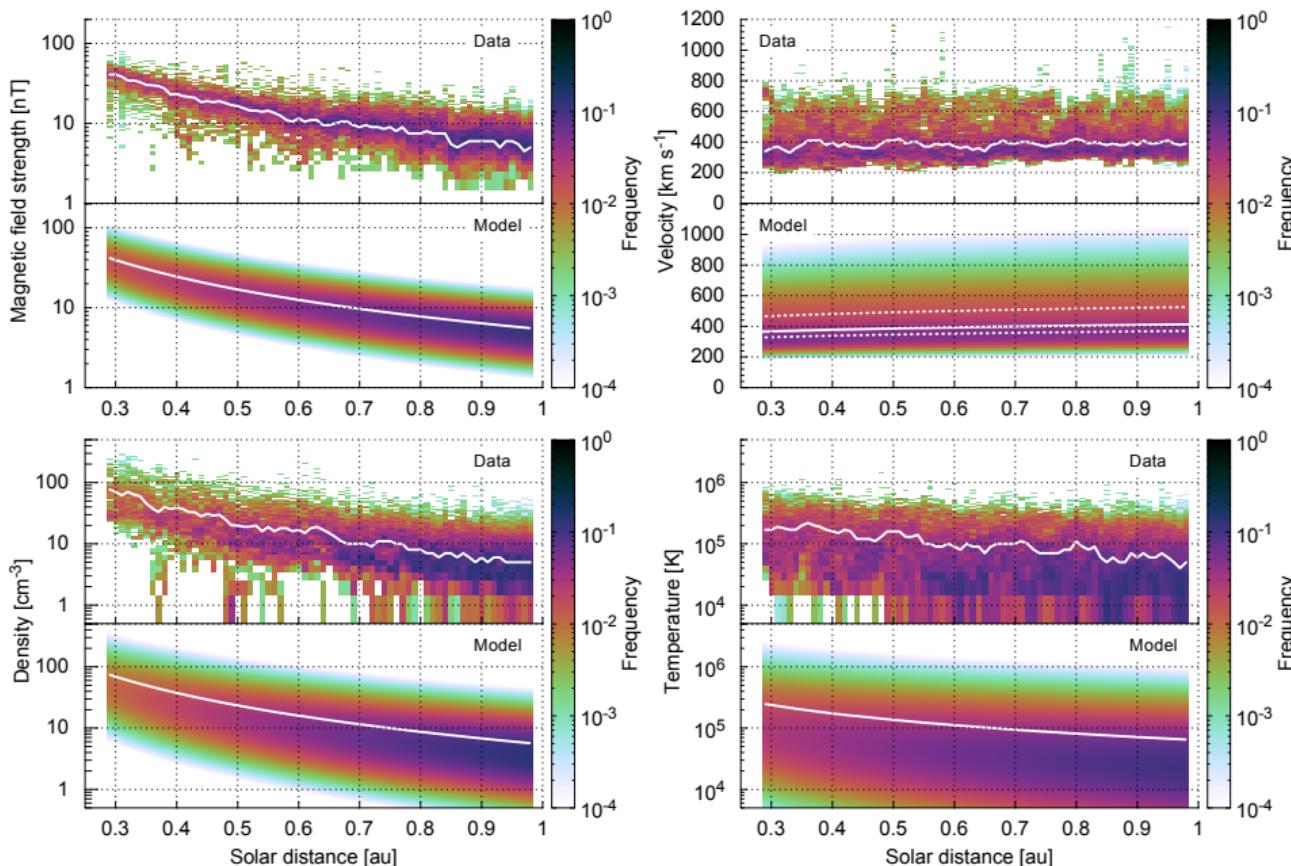


Credit: NASA

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

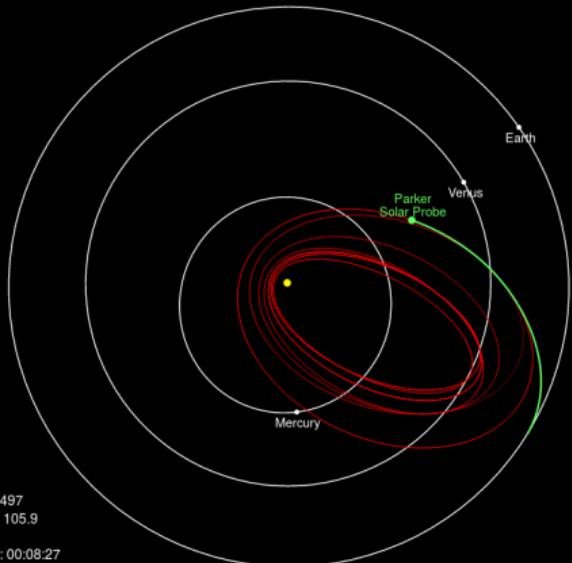


# Solar distance



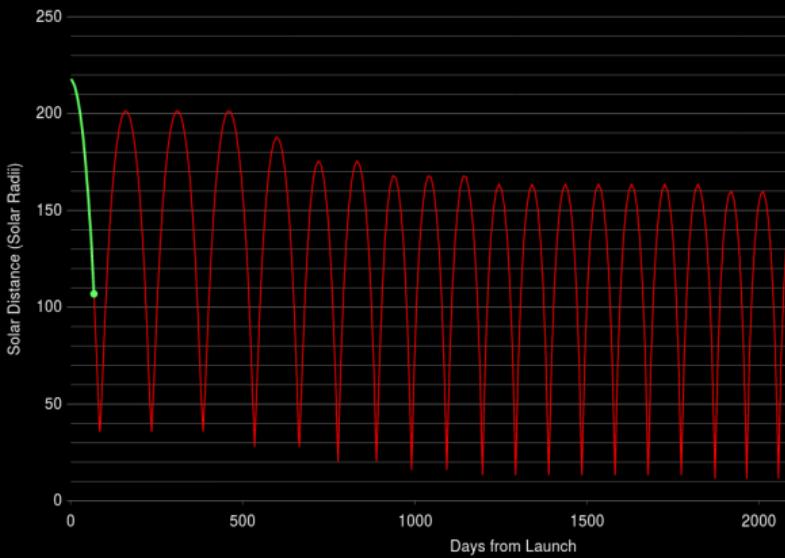
# PSP's current position

Parker Solar Probe Mission Trajectory and Current Position



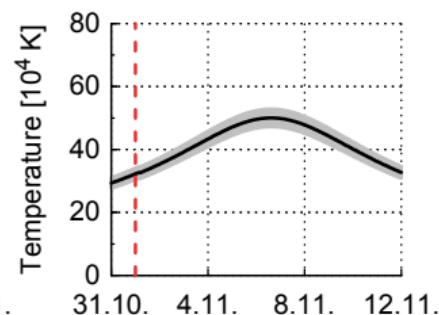
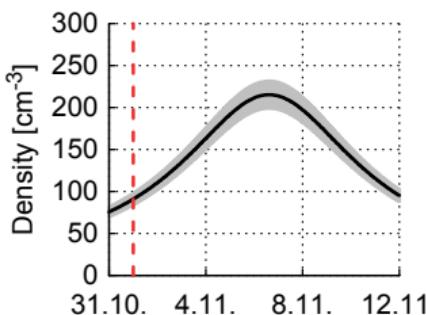
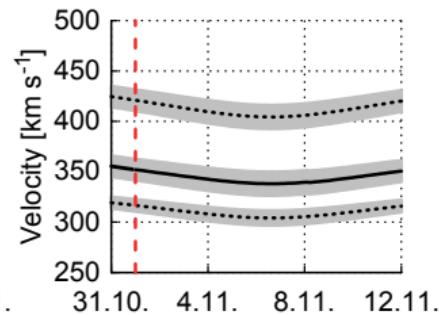
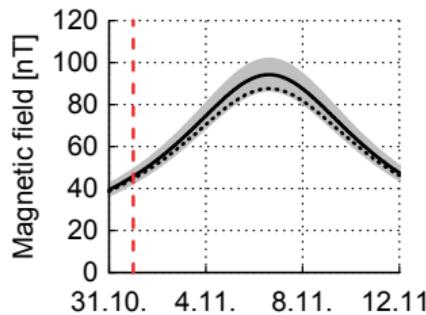
Credit: NASA

Parker Solar Probe Distance from Sun



# Prediction for PSP orbit

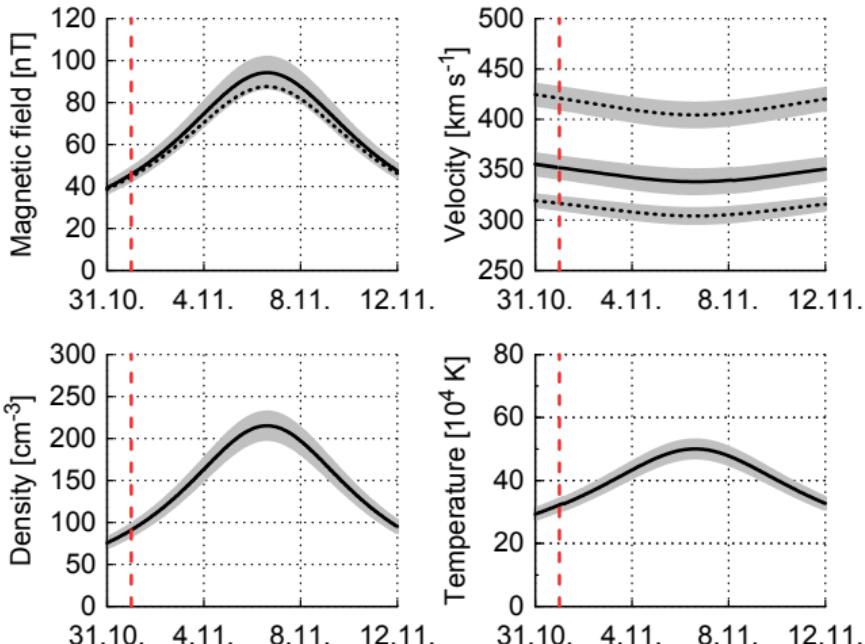
Perihelion #1



November 2018

# Prediction for PSP orbit

Perihelion #1



November 2018

Predicted values at  $36.7 R_{\odot}$

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

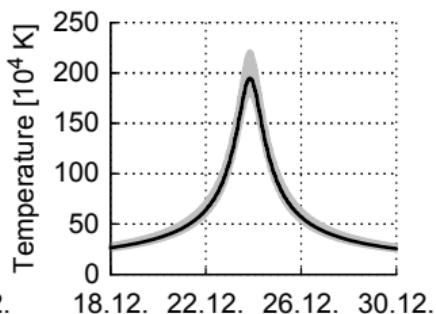
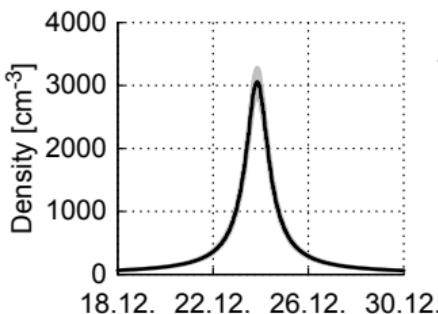
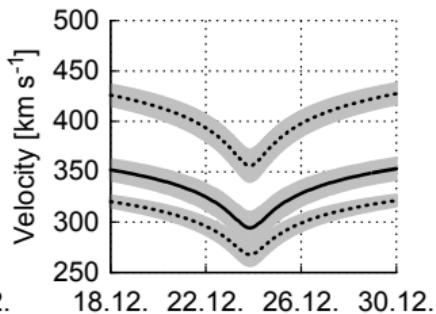
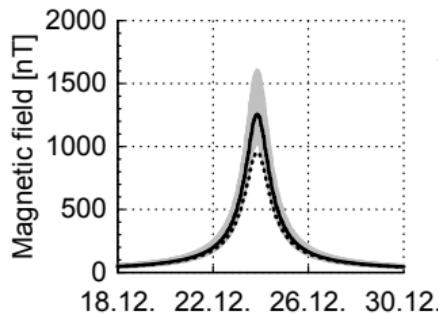
$$v = 340 \text{ km s}^{-1}$$

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

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

# Prediction for PSP orbit

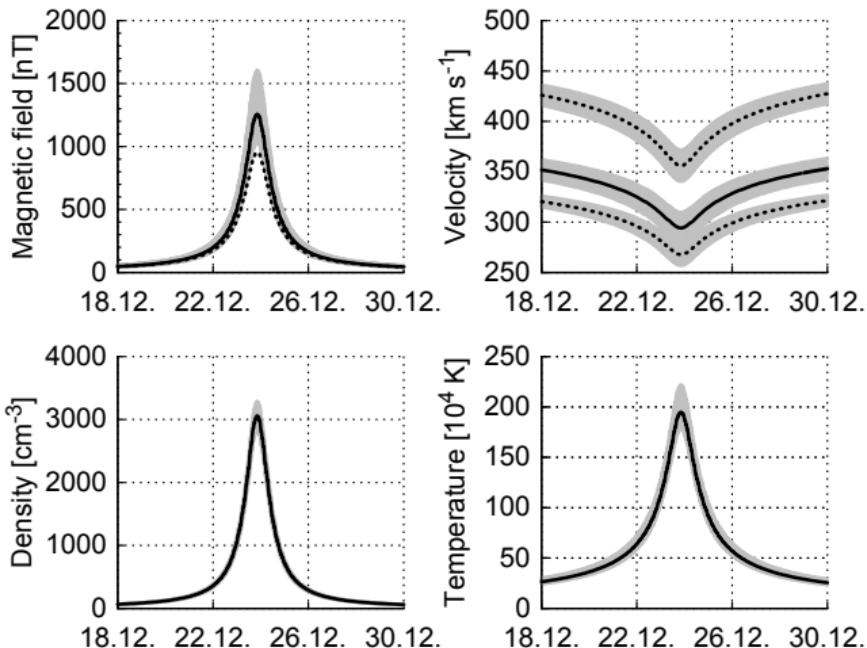
Perihelion #22 (first closest)



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 $9.86 R_{\odot}$

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

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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

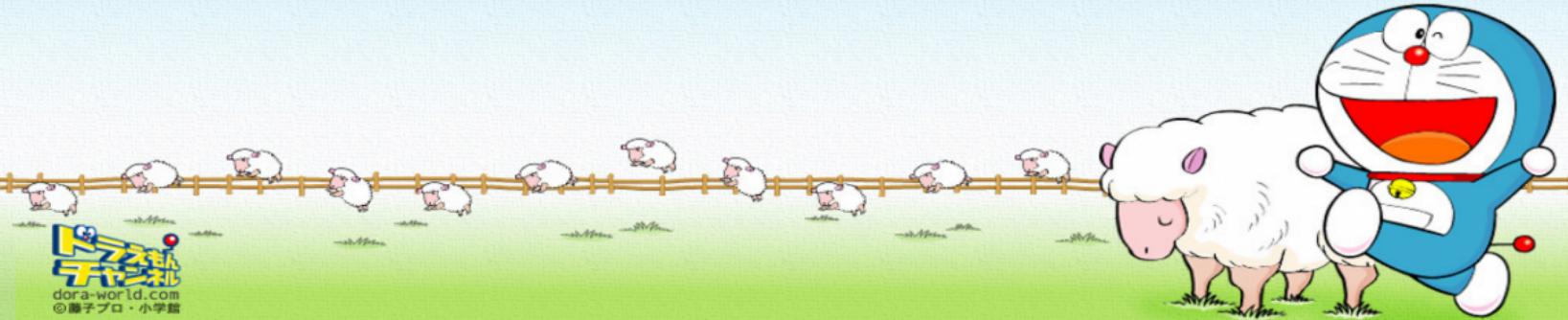
- Predictive models that relate geomagnetic disturbances with specific solar wind parameters:
  - Solar wind electric field
  - CME velocity
  - Stream velocity
- Empirical solar wind model for the inner heliosphere that considers solar activity and solar distance
  - Extrapolation of the model to the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

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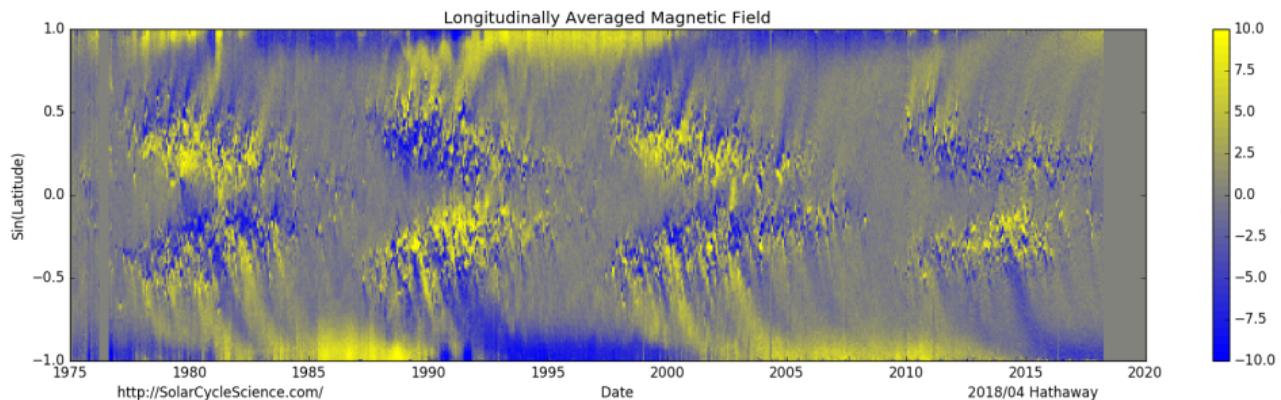


Thank you!



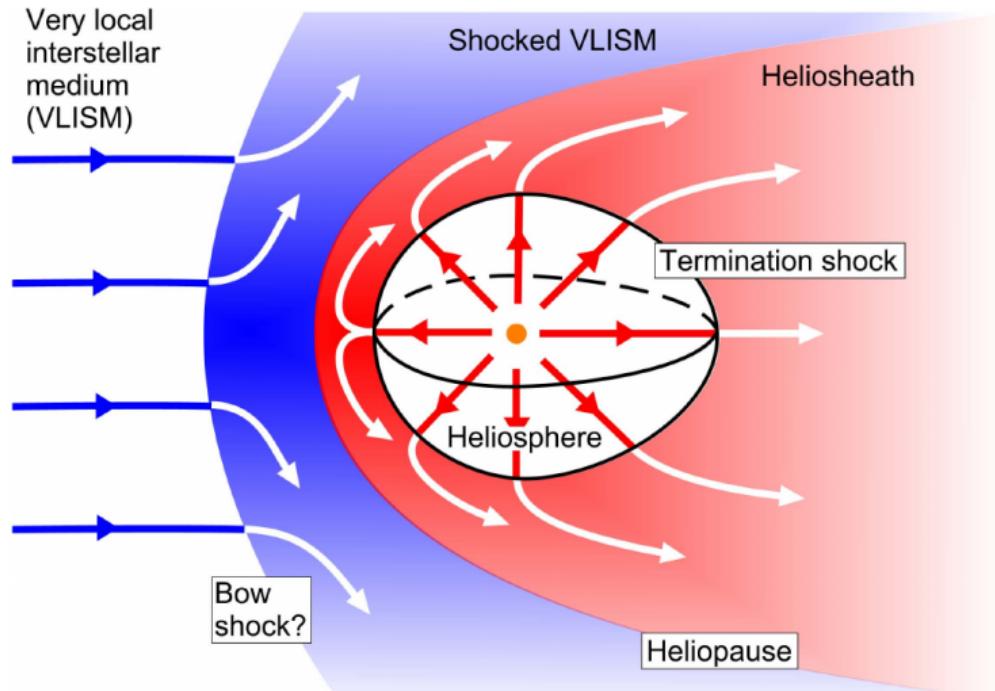
# Solar activity

## Magnetic butterfly diagram



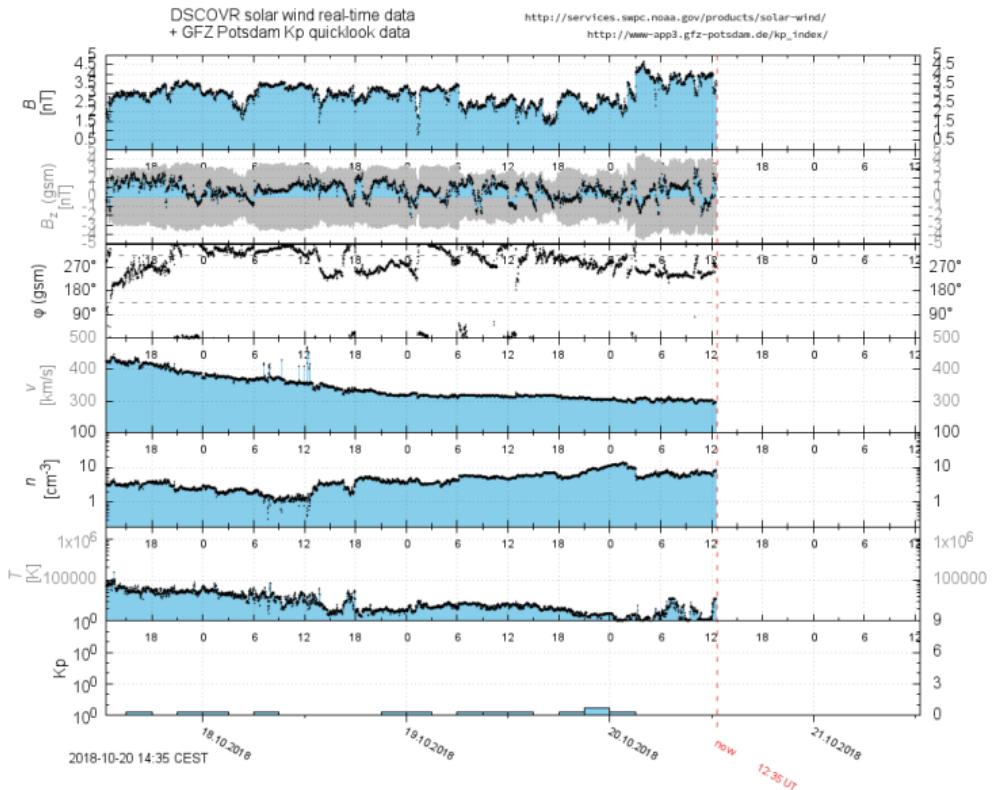
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

# Solar wind

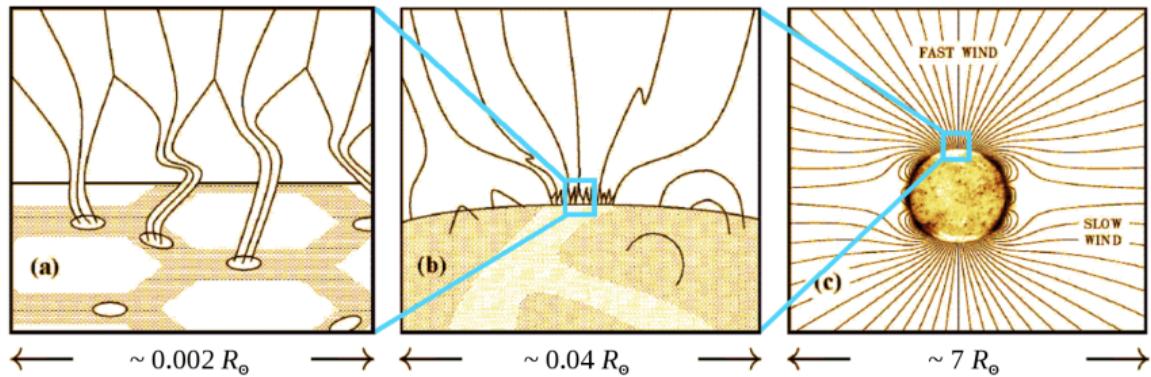


Credit: Owens & Forsyth (2013, Fig. 9)

# Solar wind

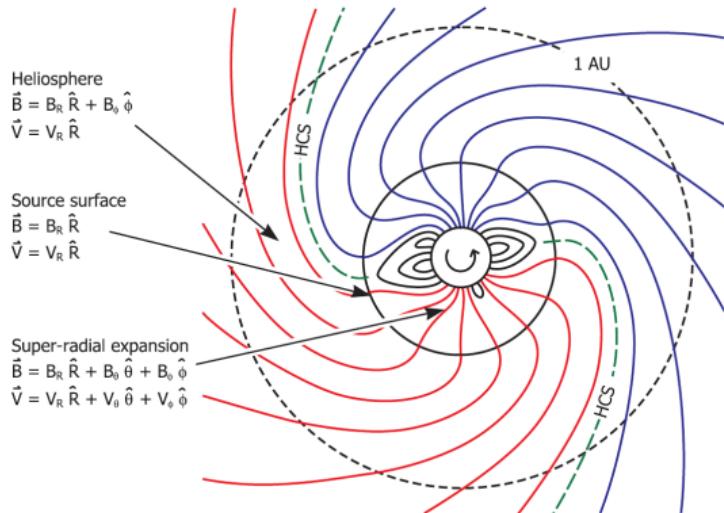


# Solar magnetic field



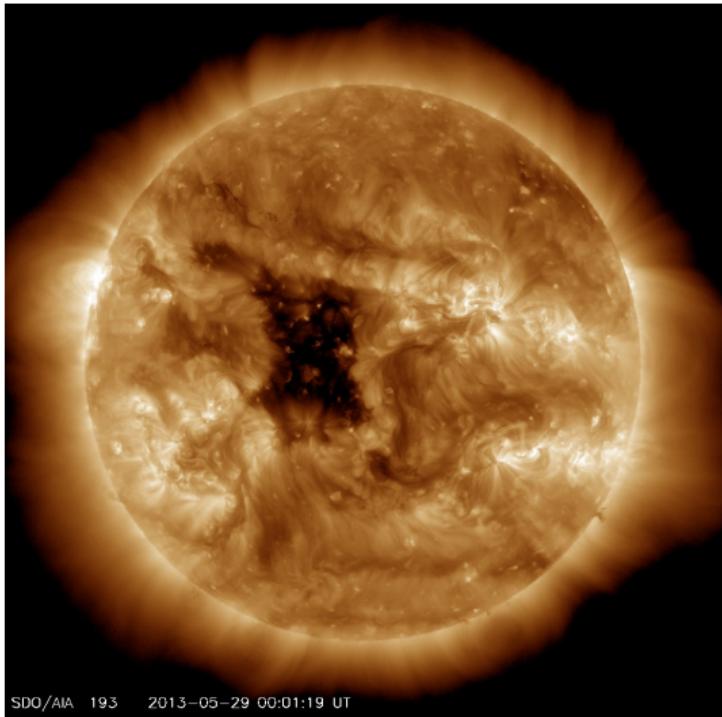
Courtesy of S. R. Cranmer

# Solar magnetic field



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

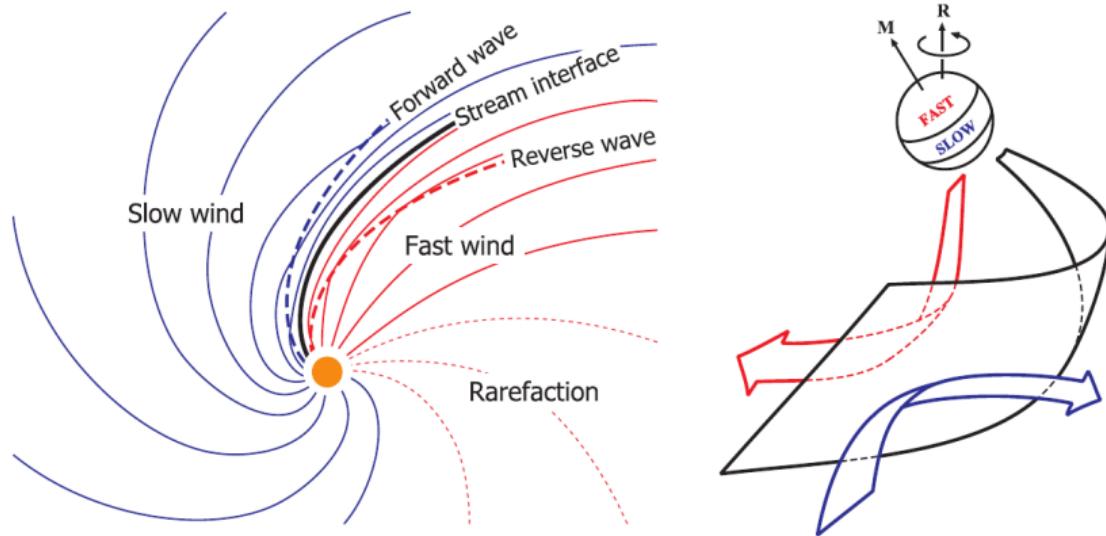
# Slow and fast solar wind



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

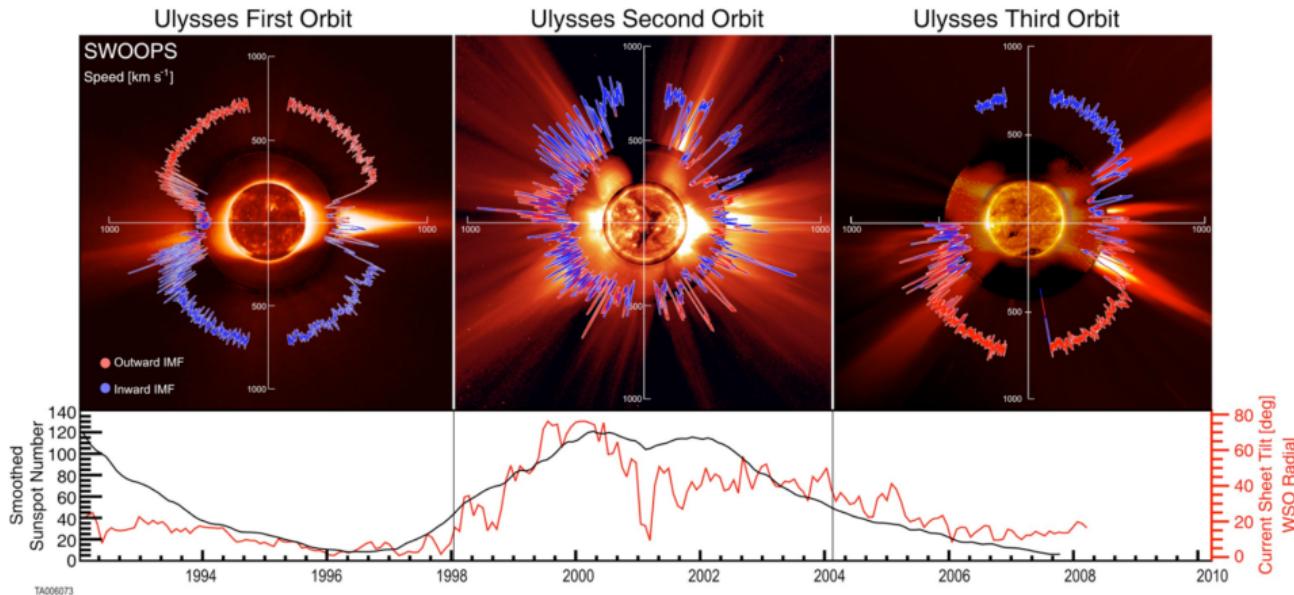
Credit: NASA/SDO and the AIA, EVE and HMI science teams

# Slow and fast solar wind



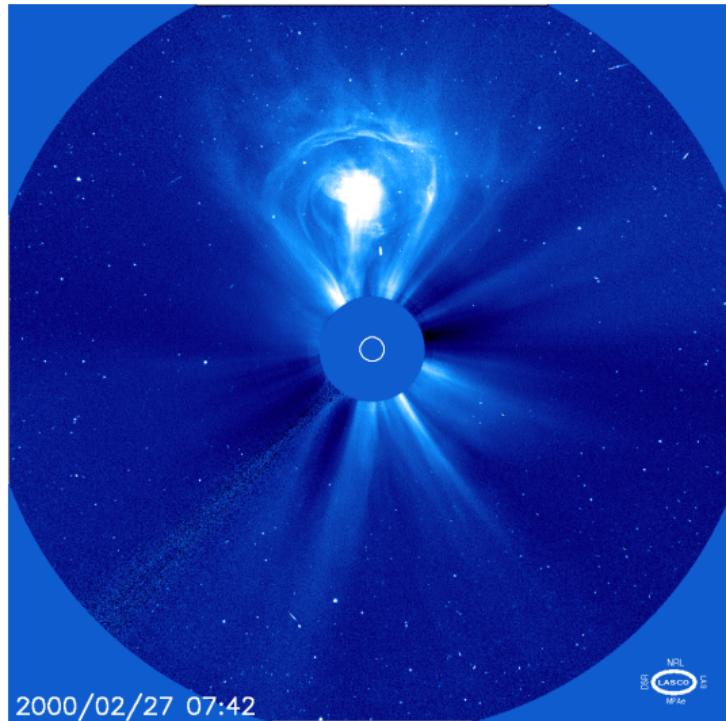
Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

# Solar activity



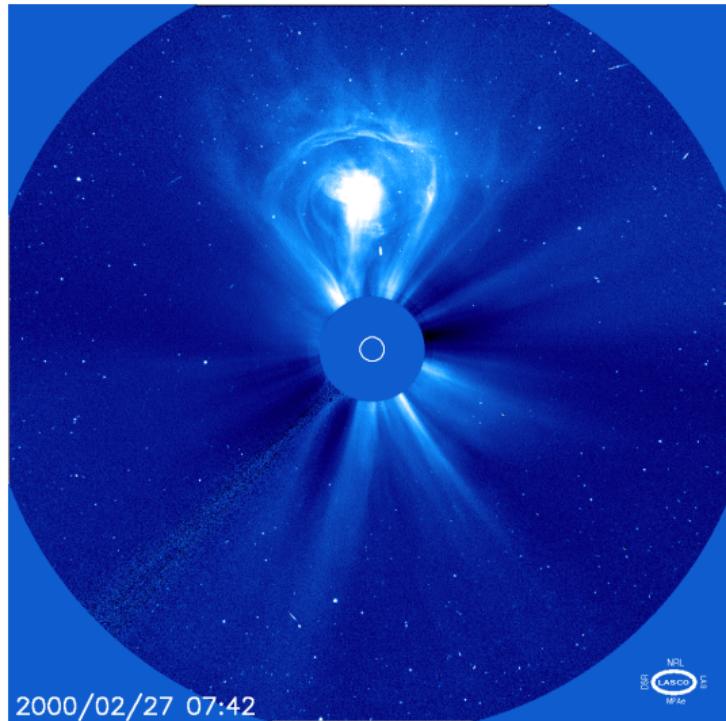
Credit: McComas et al. (2008a, Fig. 1)

# Coronal mass ejections

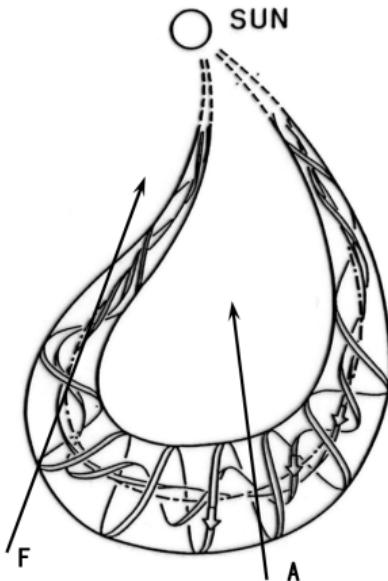


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

# Coronal mass ejections

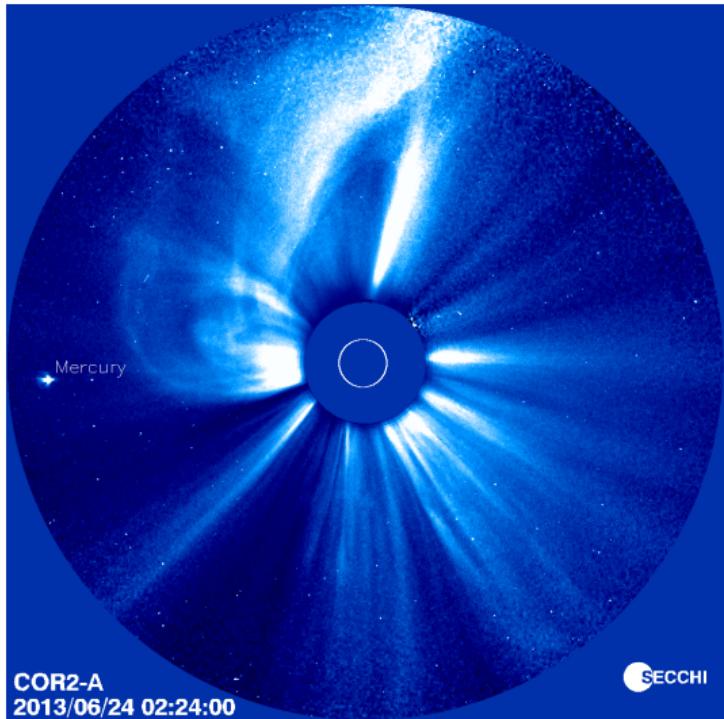


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

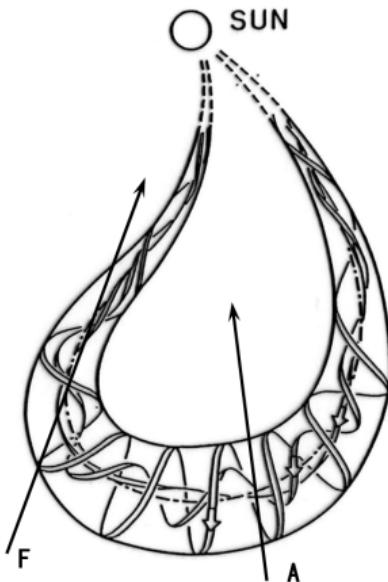


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# Coronal mass ejections

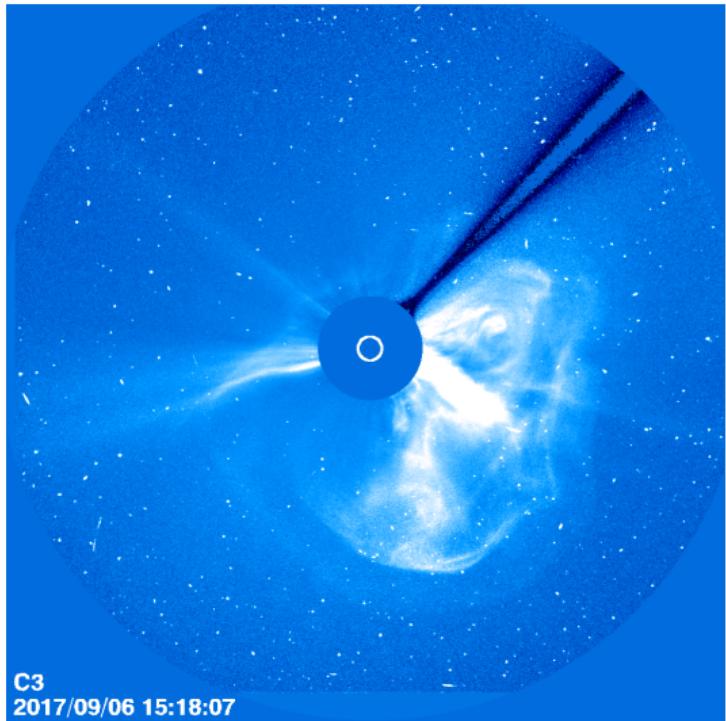


Courtesy of STEREO/COR2 consortium (NASA)



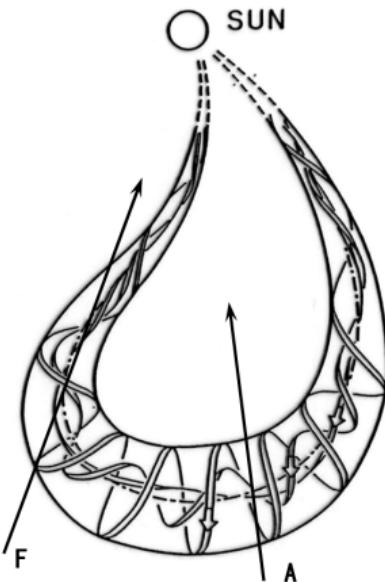
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# Coronal mass ejections



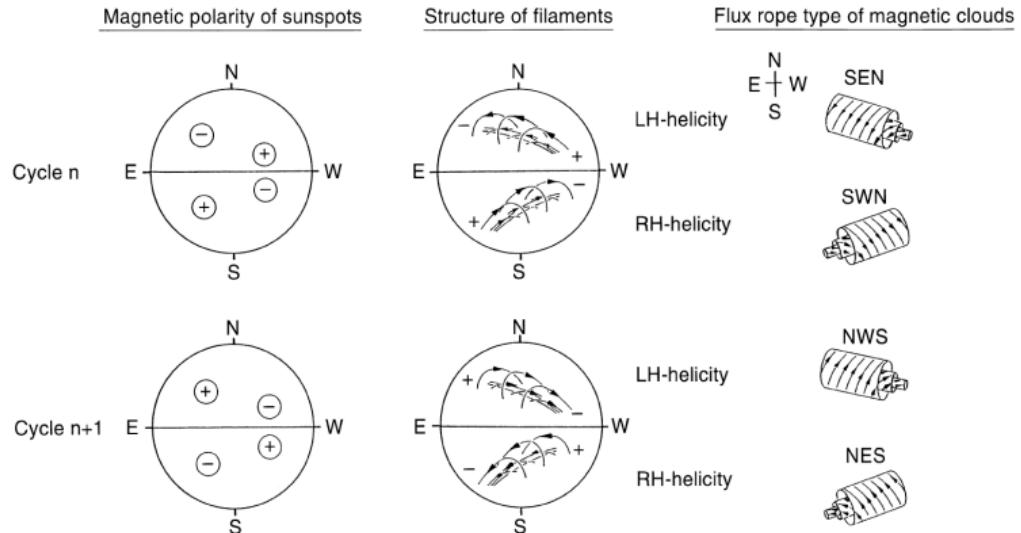
C3  
2017/09/06 15:18:07

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



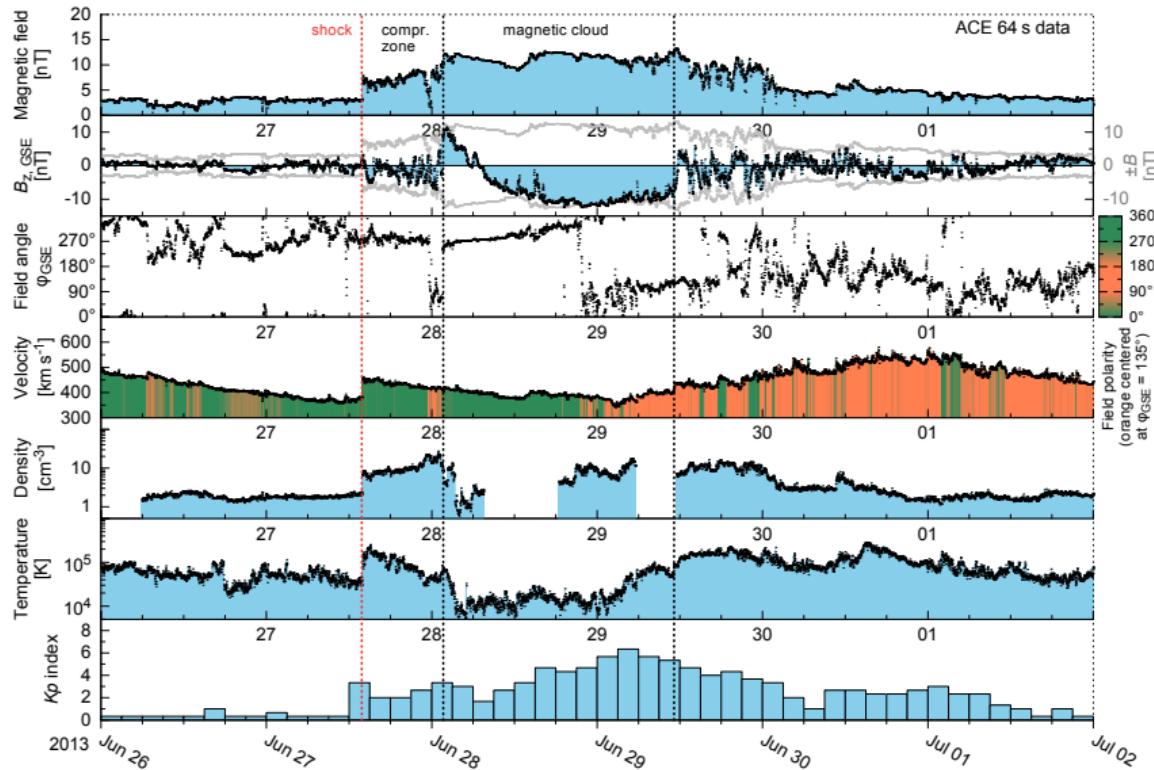
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

# CME orientation

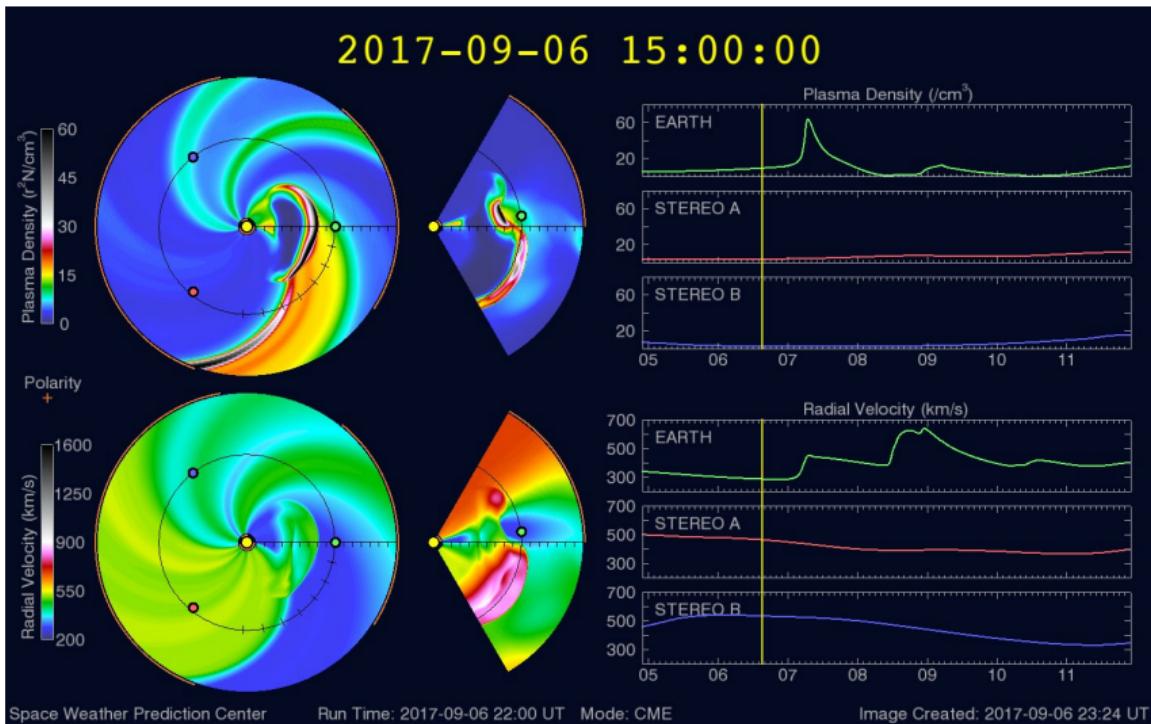


Credit: Bothmer & Schwenn (1998, Fig. 18)

# In-situ CMEs

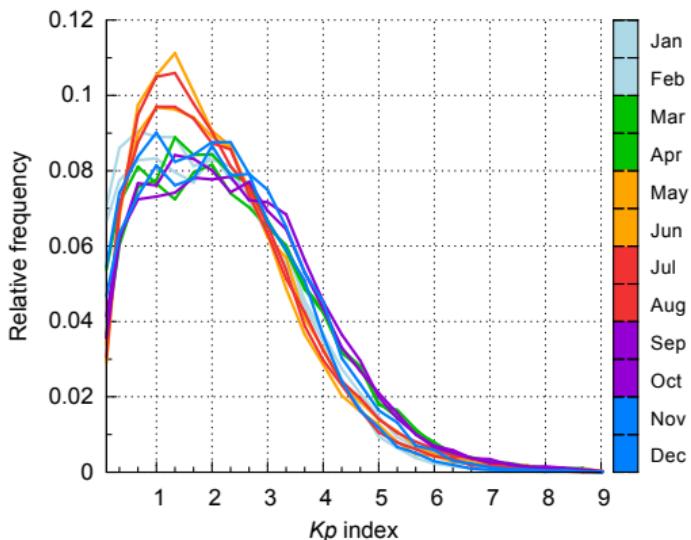
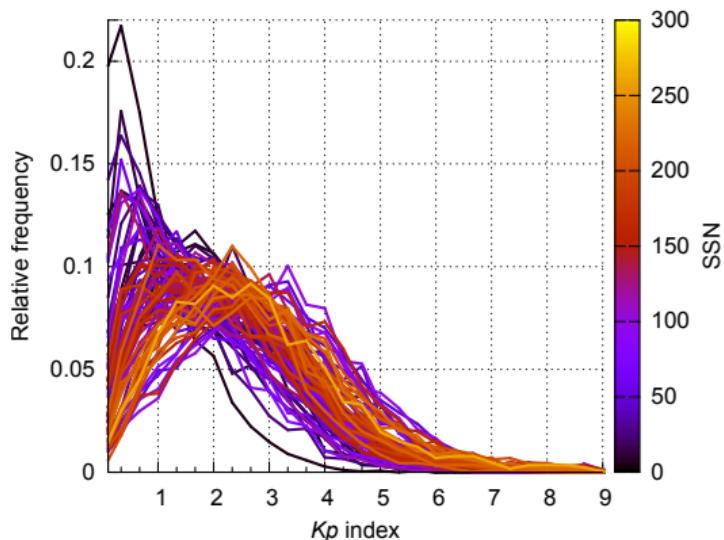


# Solar wind and CME forecast

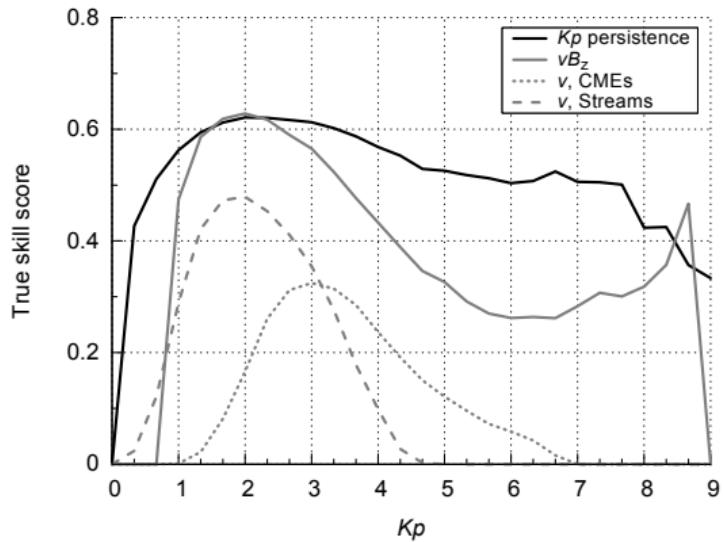
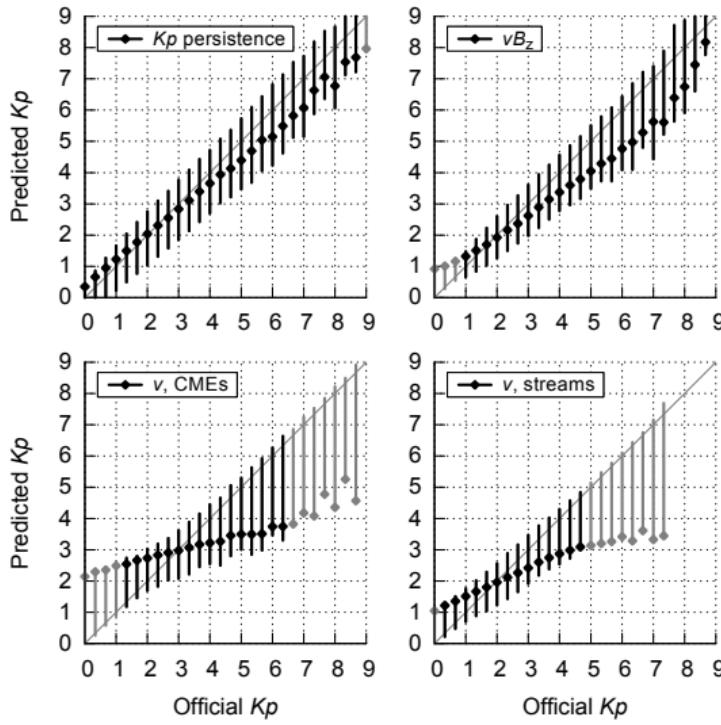


Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

## $Kp$ long-term variations



# Prediction performance

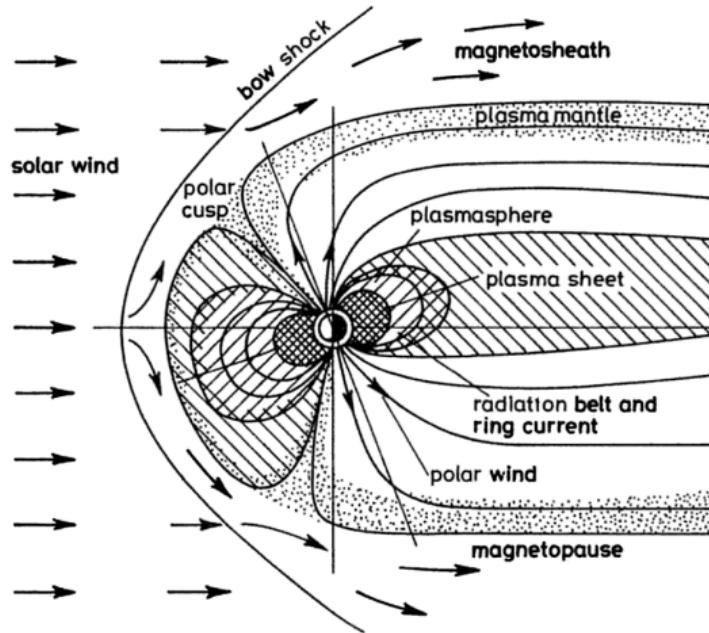


# Geomagnetic impact of the solar wind

## Aims

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

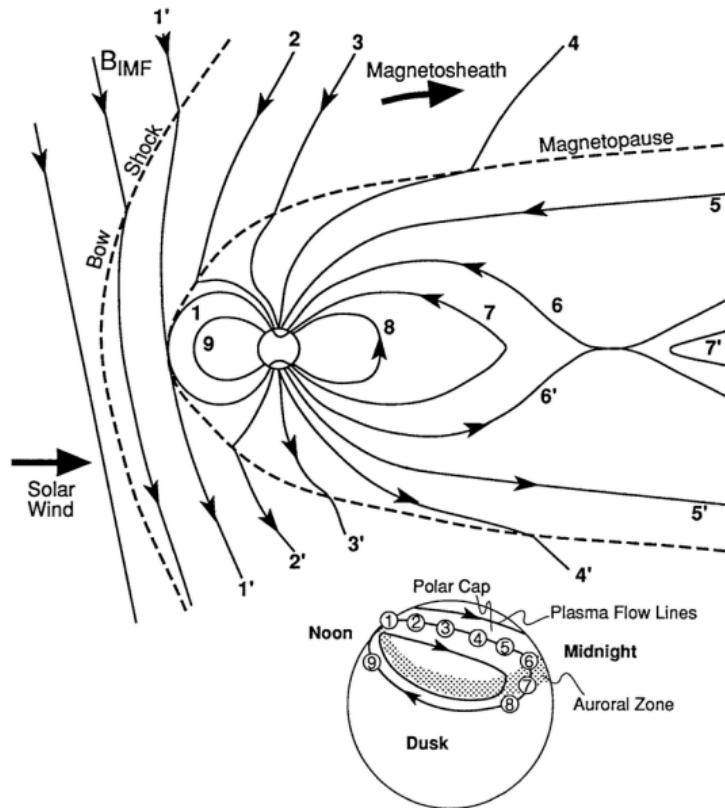
# Magnetosphere



Credit: Davies (1990, Fig. 2.12)

4 interaction mechanisms

# Magnetosphere

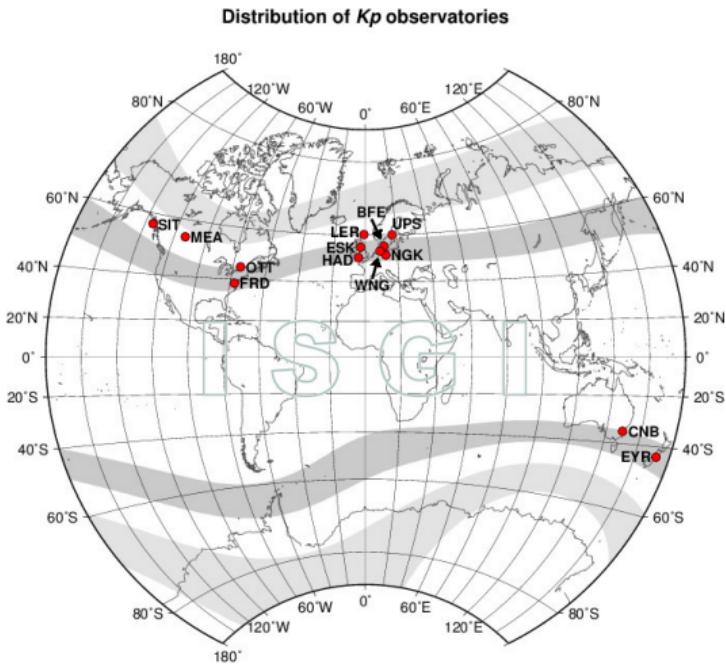


Credit: Hughes (1995, Fig. 9.11)

4 factors for merging flux rate

# *Kp* index

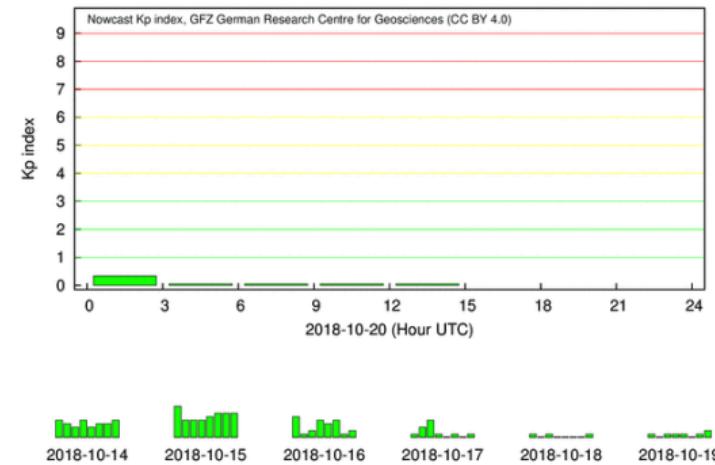
13 observatories...



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

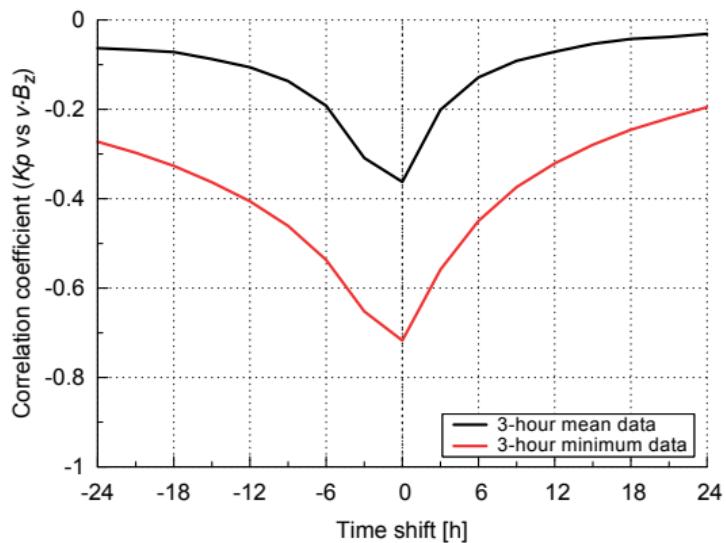
# *Kp* index

## Quicklook *Kp*

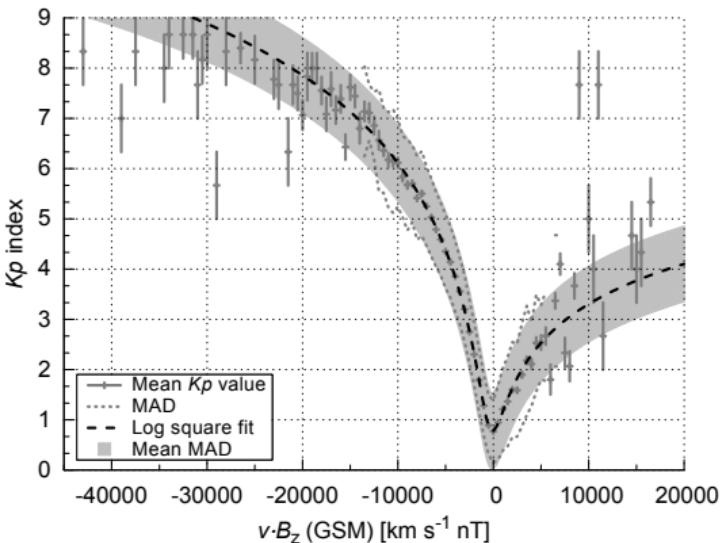
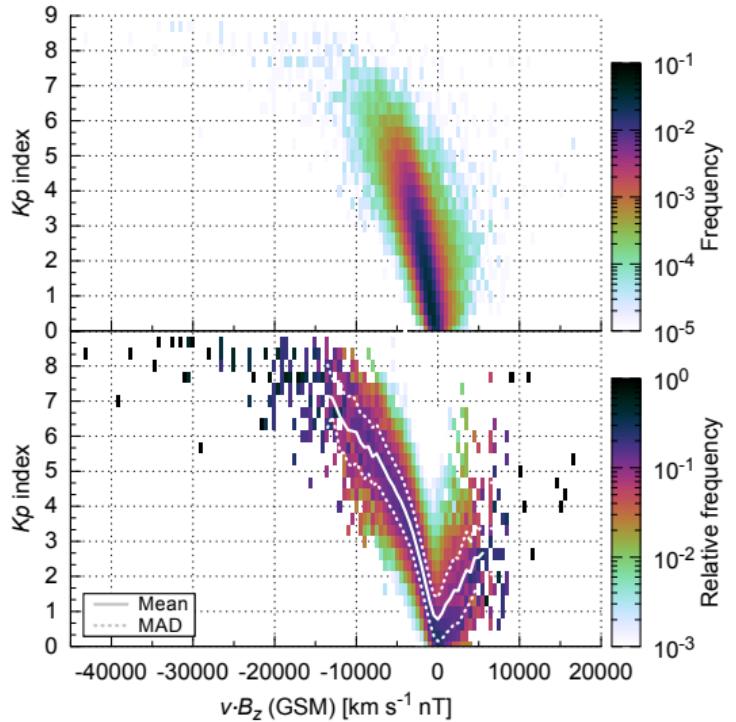


Credit: GFZ Potsdam, 2018

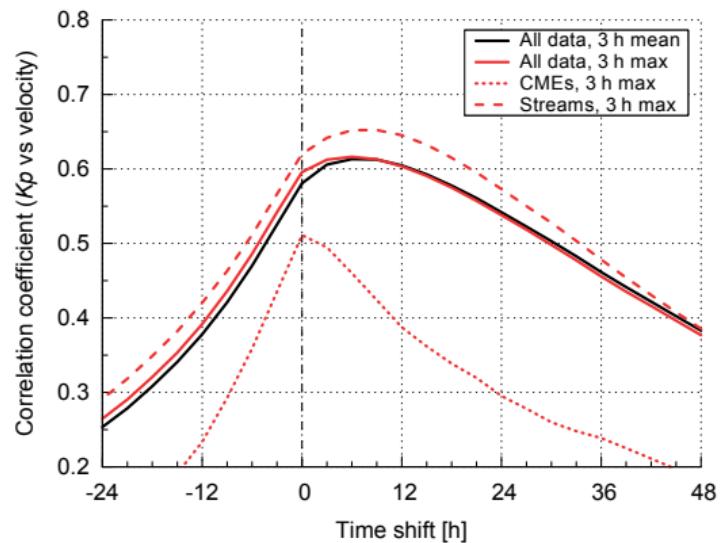
## Solar wind electric field



# Solar wind electric field



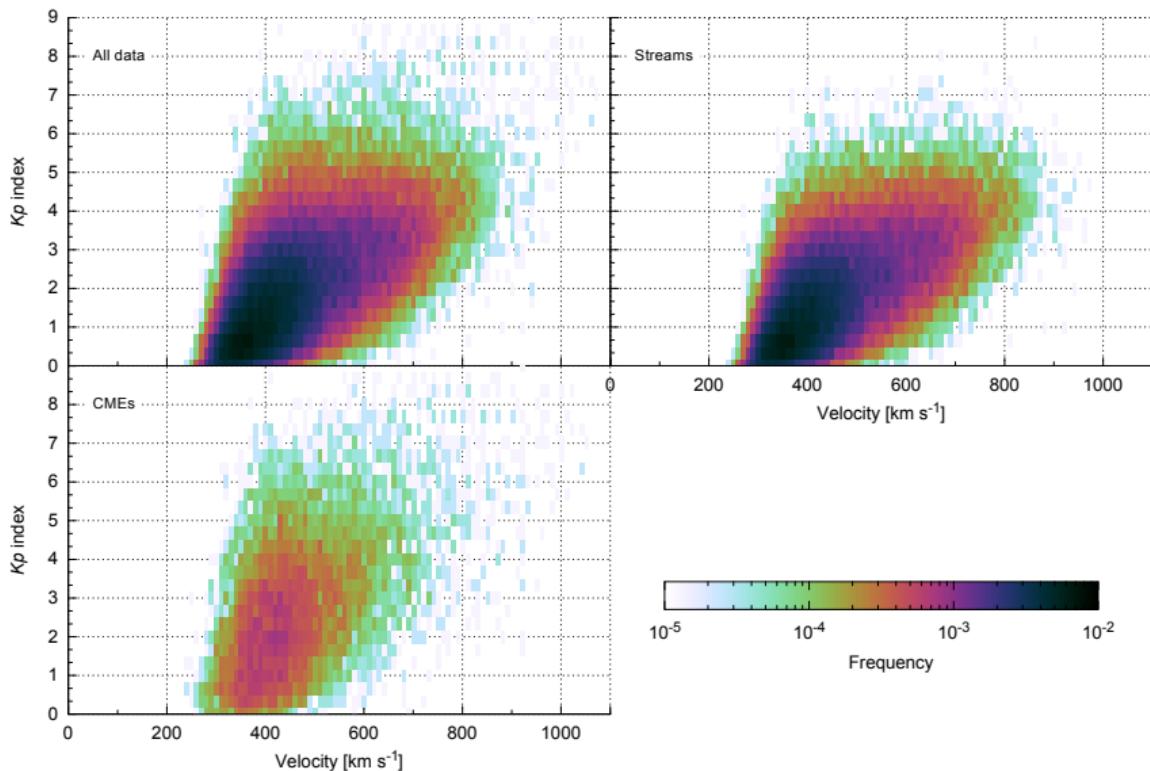
# Solar wind velocity

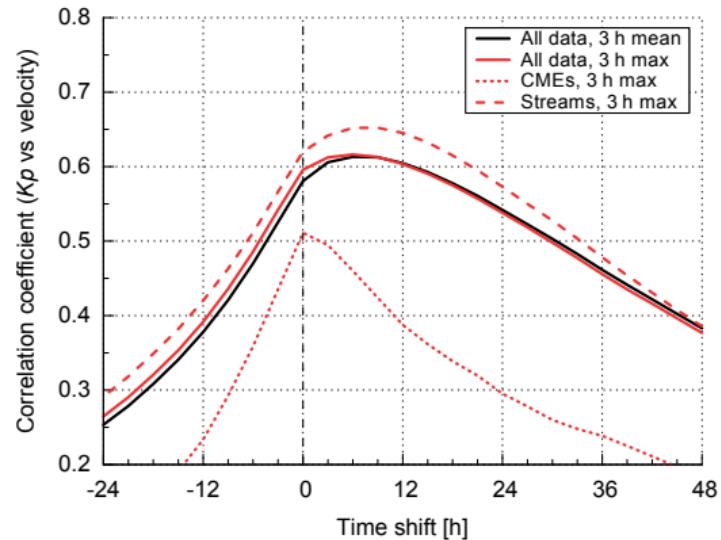


## Solar wind velocity

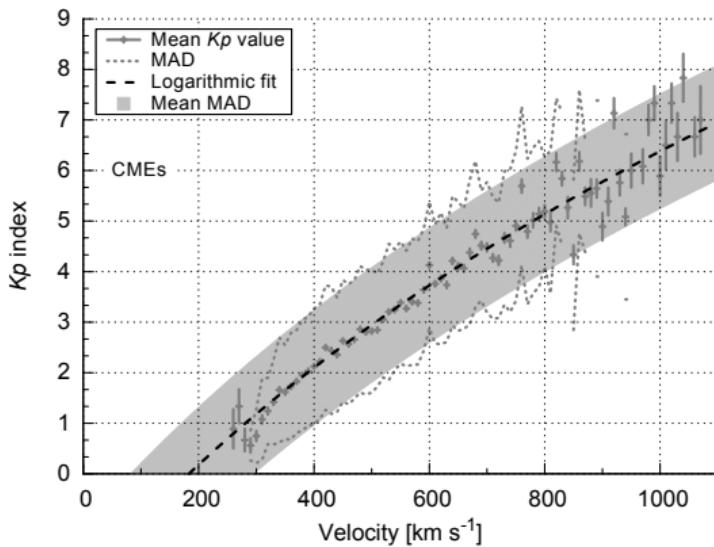
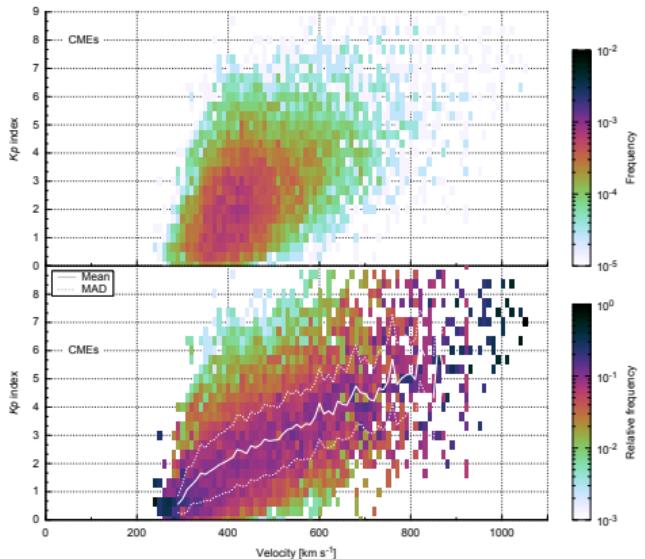
CME – stream separation  
Solar Wind Structures list

# Solar wind velocity

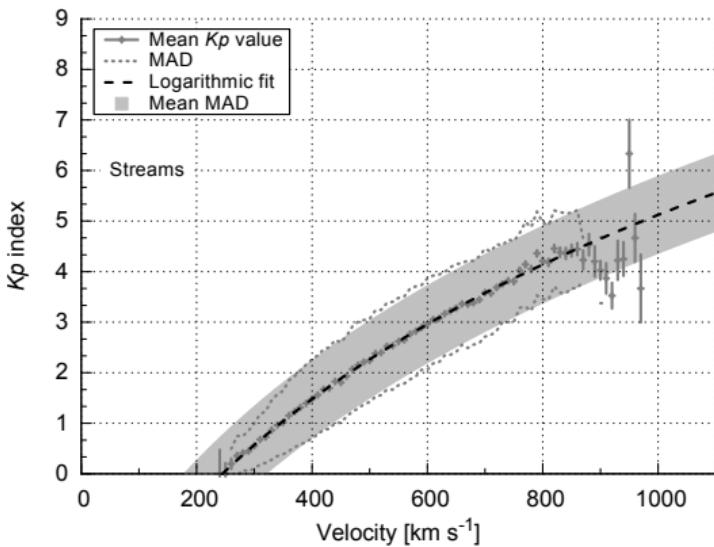
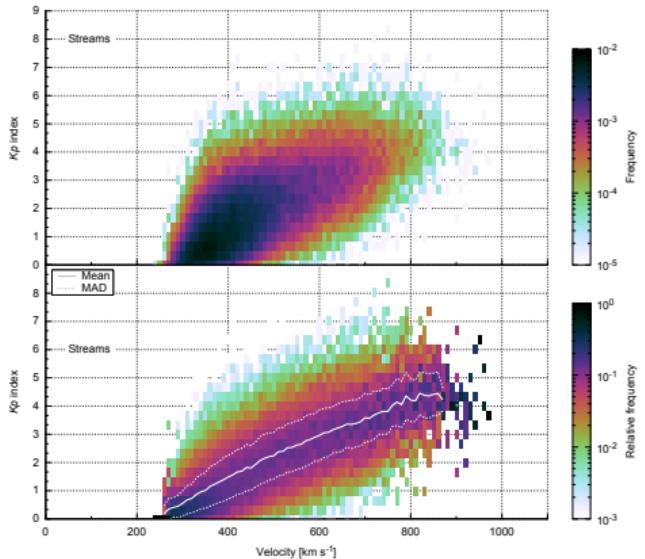


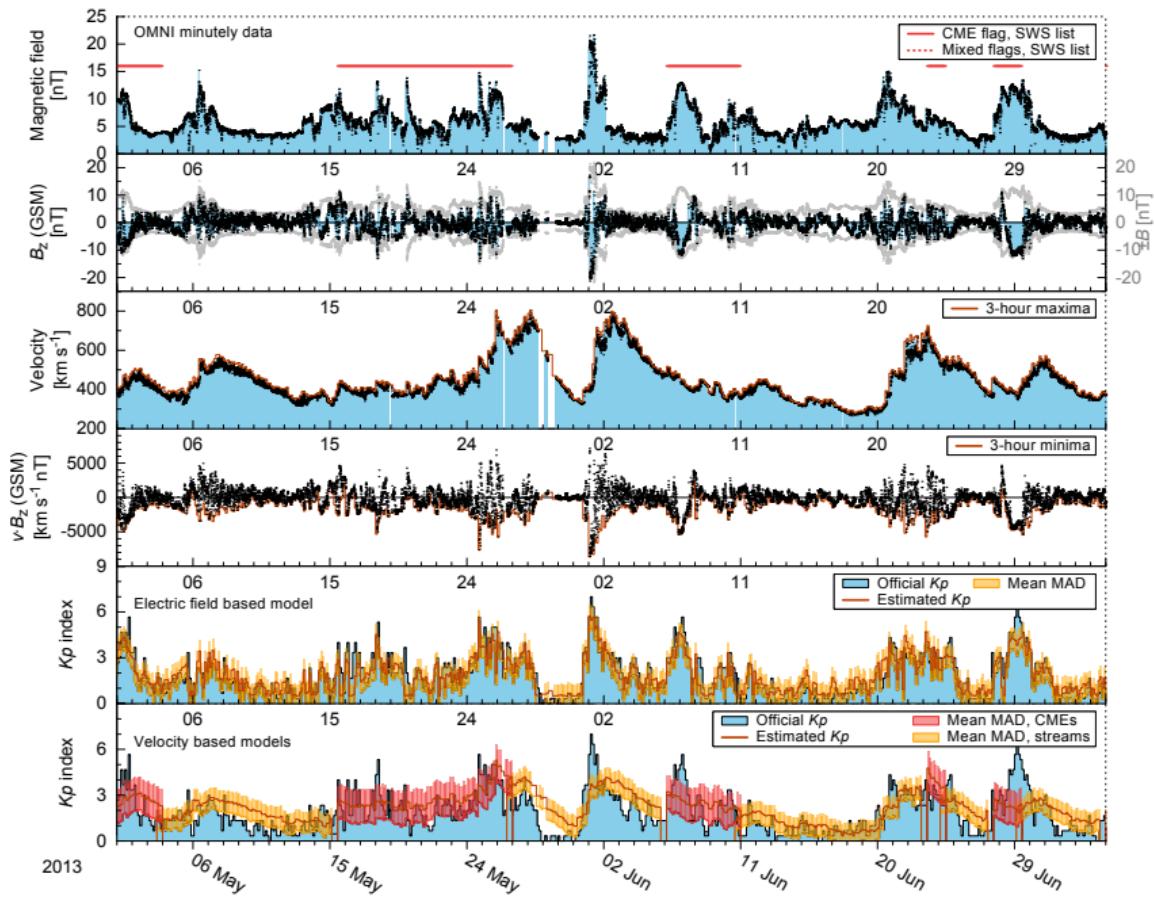


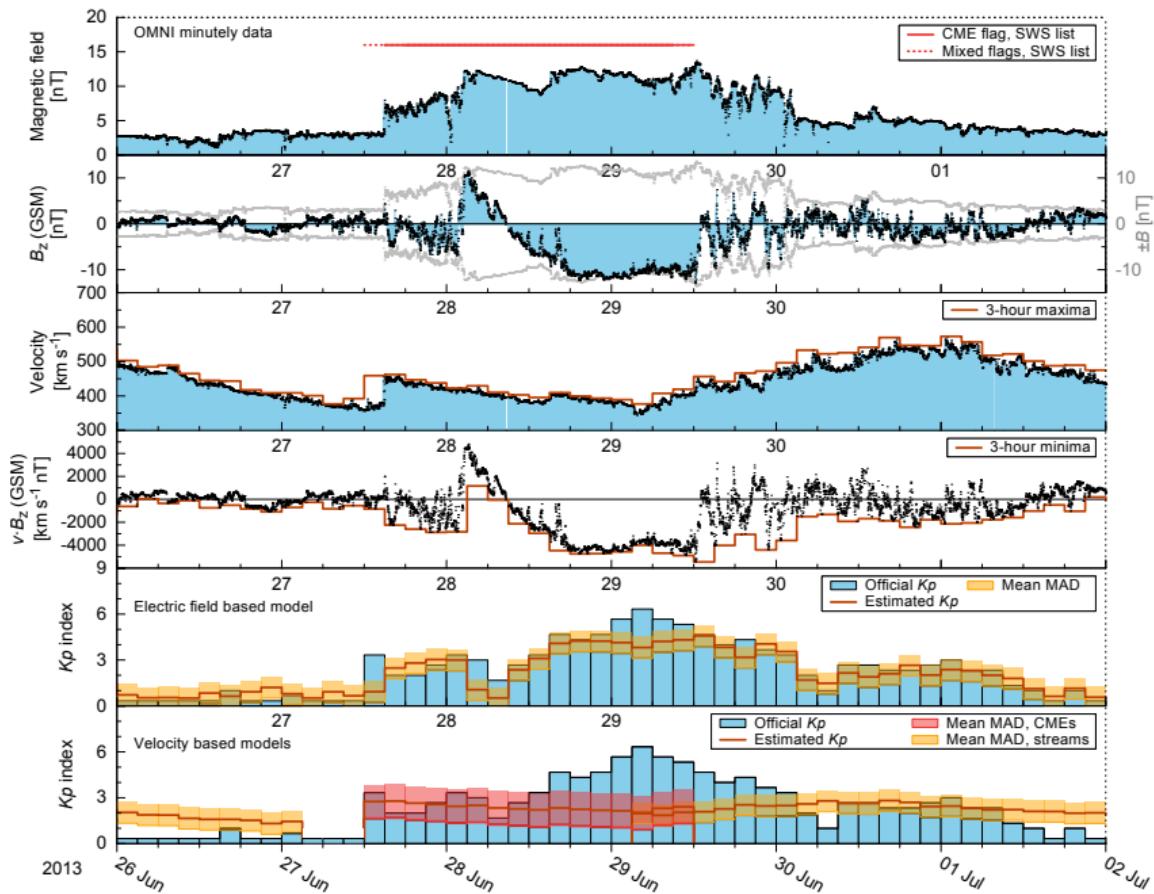
# CME velocity



# Stream velocity







## Results

Predictive  $K_p$  models based on relations with

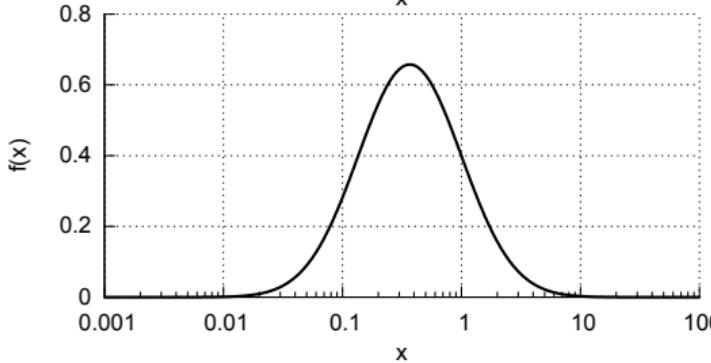
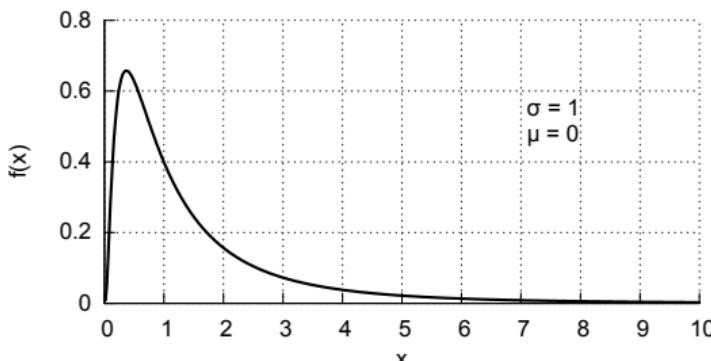
- solar wind electric field proxy ( $vB_z$ )
- velocity of CME-associated flows ( $v_{\text{CME}}$ )
- velocity of solar wind streams ( $v_{\text{stream}}$ )

## 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 ( $\sigma$ ).

Median and average:

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

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

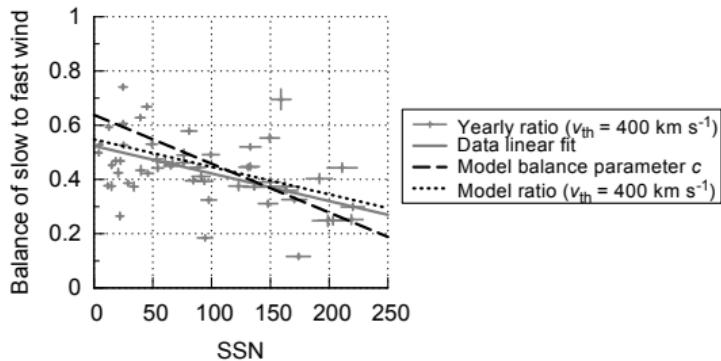
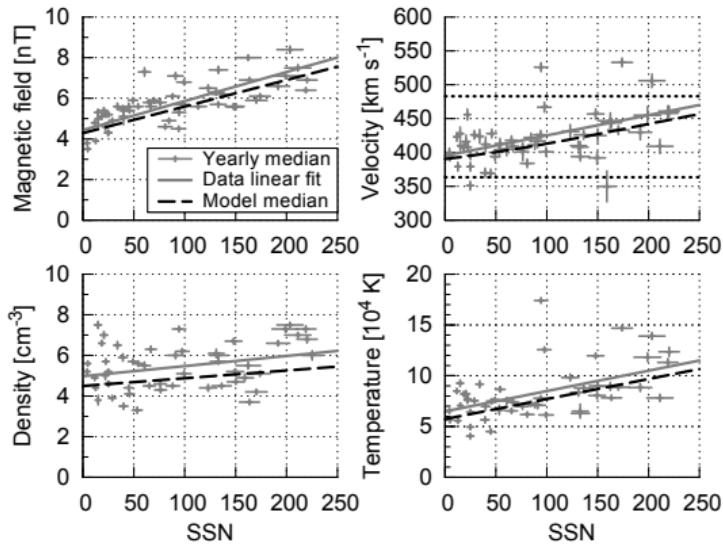
## Sun–Earth evolution of the solar wind

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

