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

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

PhD defense by *Malte Venzmer*

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Thursday, 1 November 2018, 14:00

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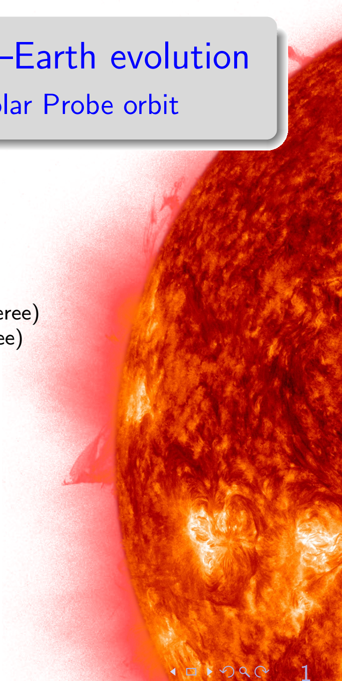

The two studies in my thesis

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

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- Velocity of coronal mass ejections
- Velocity of solar wind streams

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- Solar wind model for the inner heliosphere
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  - Solar activity
  - Solar wind
  - Parker Solar Probe (PSP)
- Empirical solar wind model
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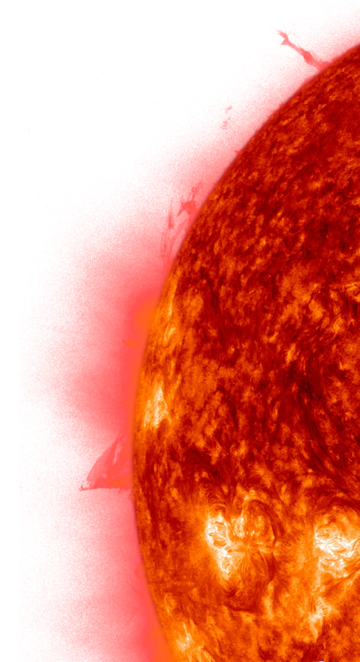

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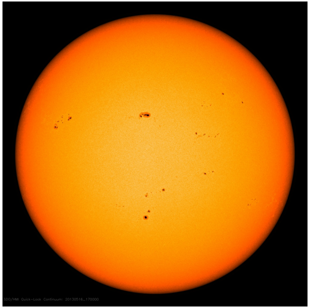
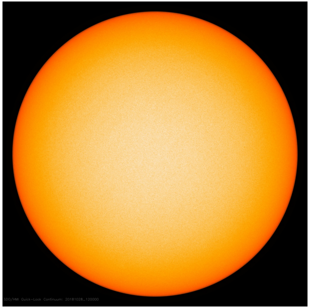
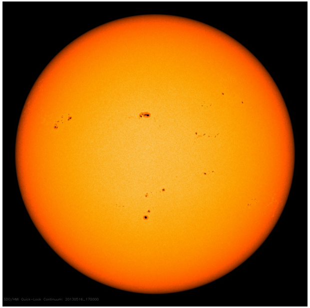


Credit: NASA SDO/HMI, 16 May 2013



Credit: NASA SDO/HMI, 28 October 2018



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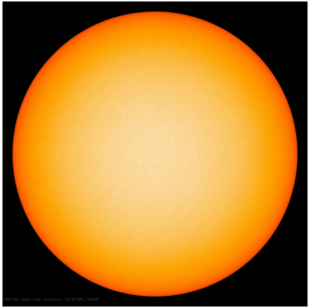

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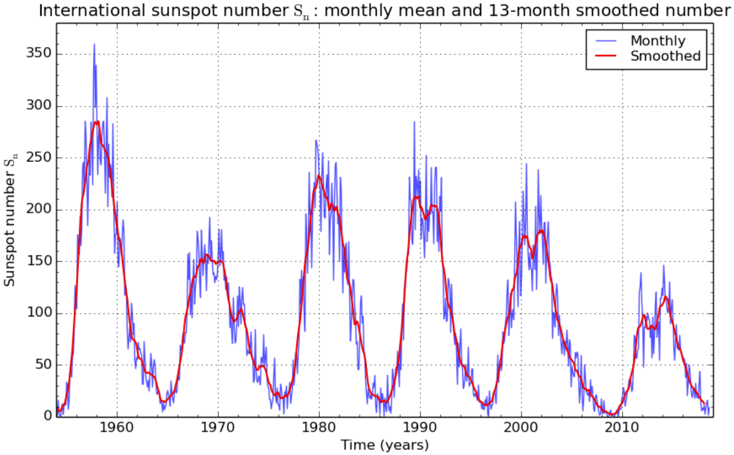
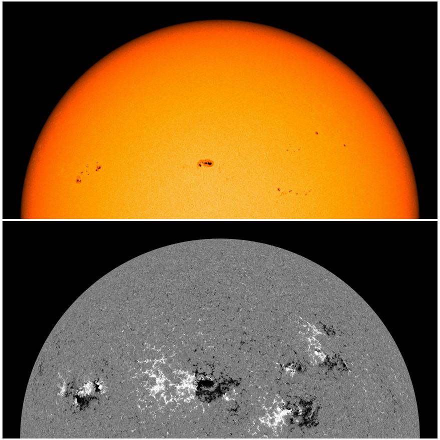
Sunspot number:
11-year periodicity – solar cycle



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

Solar activity



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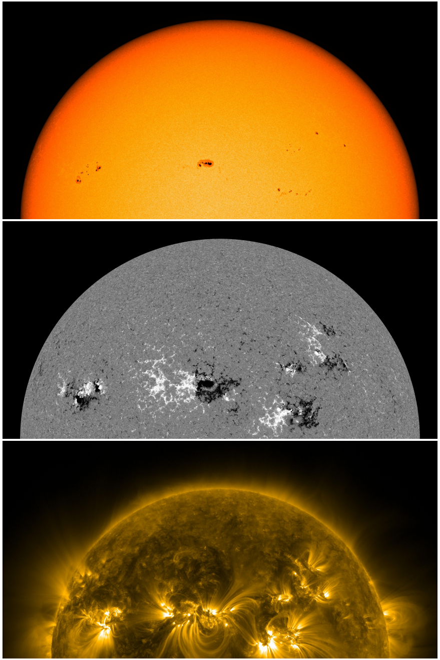

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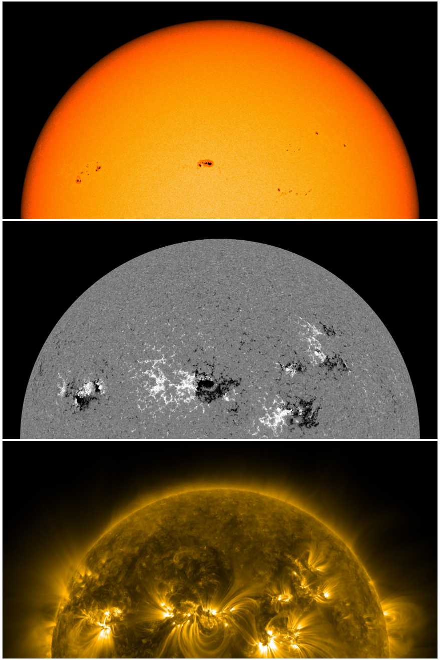

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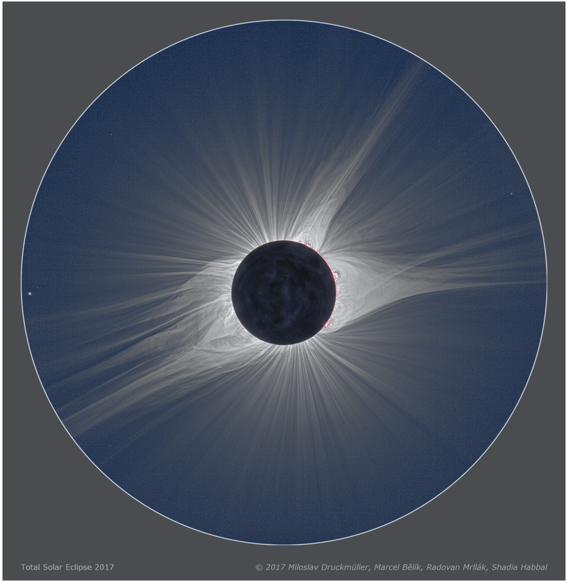

Credit: Miloslav Druckmüller, Marcel Bělík, Radovan Mrllák, Shadia Habbal, 2017

Solar wind

Solar wind

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

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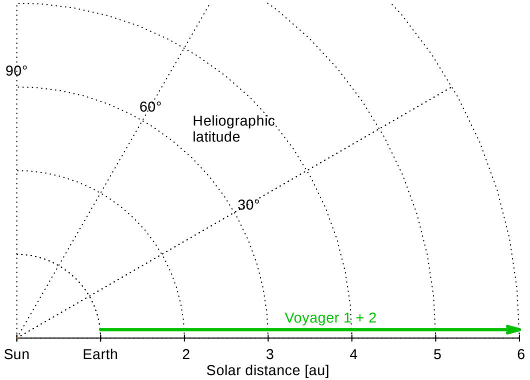
- Voyager 1 & 2 – out to heliopause (1–120 au)



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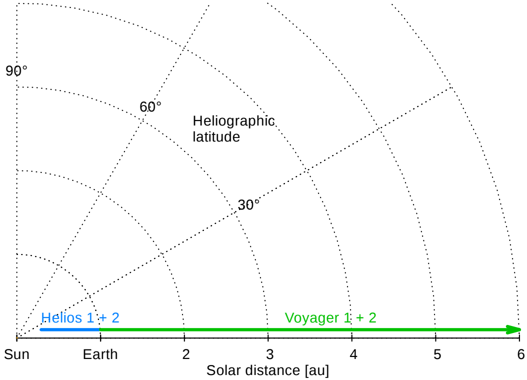

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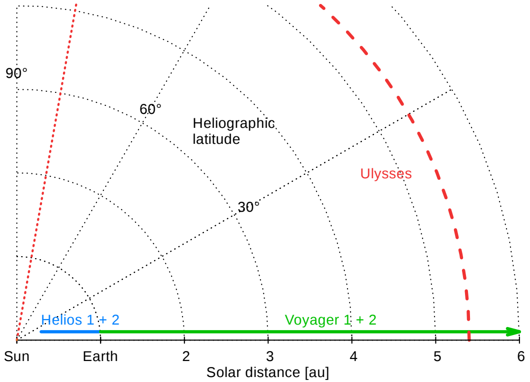

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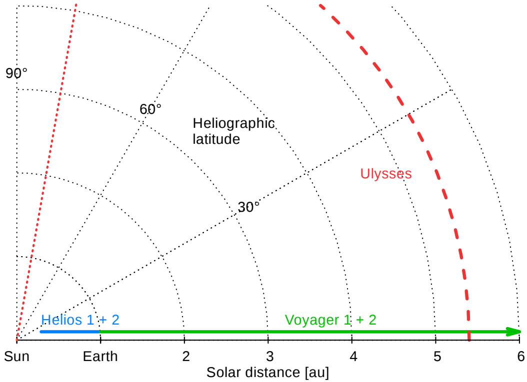

Different types of solar wind:

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

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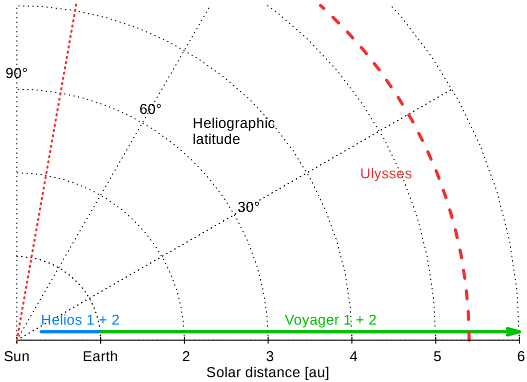

Different types of solar wind:

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

$\Rightarrow$ Their share varies with solar activity

Solar wind

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

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

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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

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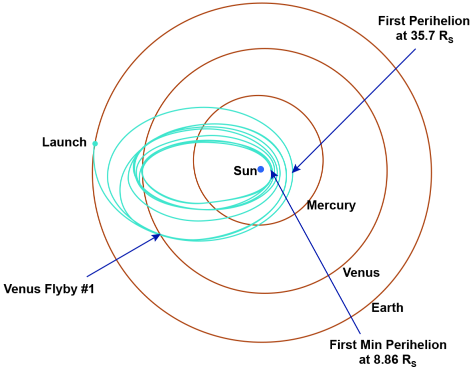

Credit: NASA/Johns Hopkins APL, 2018

Launch	12 August 2018
1st Venus flyby	3 October
1st perihelion at 36.7 $R_\odot$	6 November
…	…
22nd perihelion at 9.86 $R_\odot$	24 December 2024

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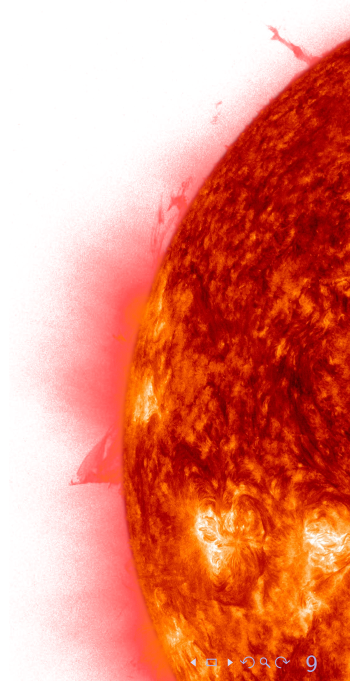

Empirical solar wind model

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

Solar wind environment (key parameters)

- Magnetic field strength
- Velocity
- Density
- Temperature

Concept of the model:

- use existing solar wind measurements
- build empirical solar wind model
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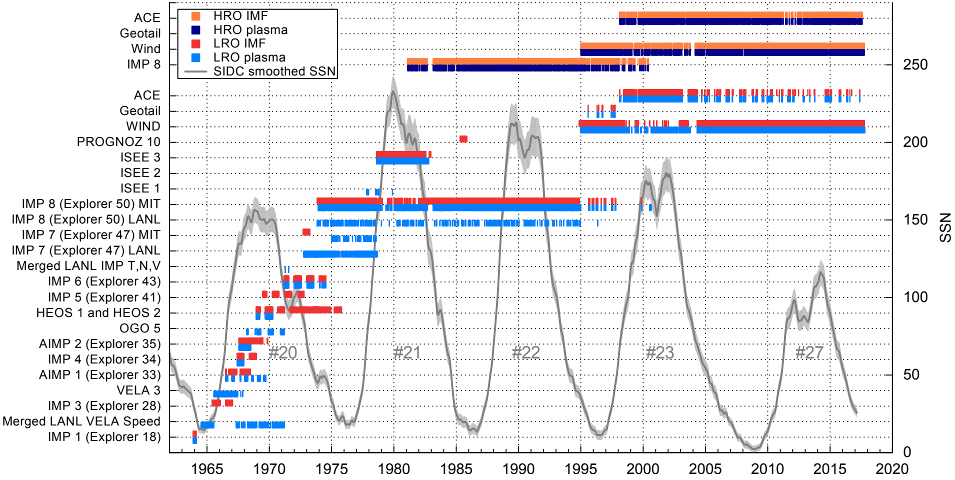
Uniqueness of the model:

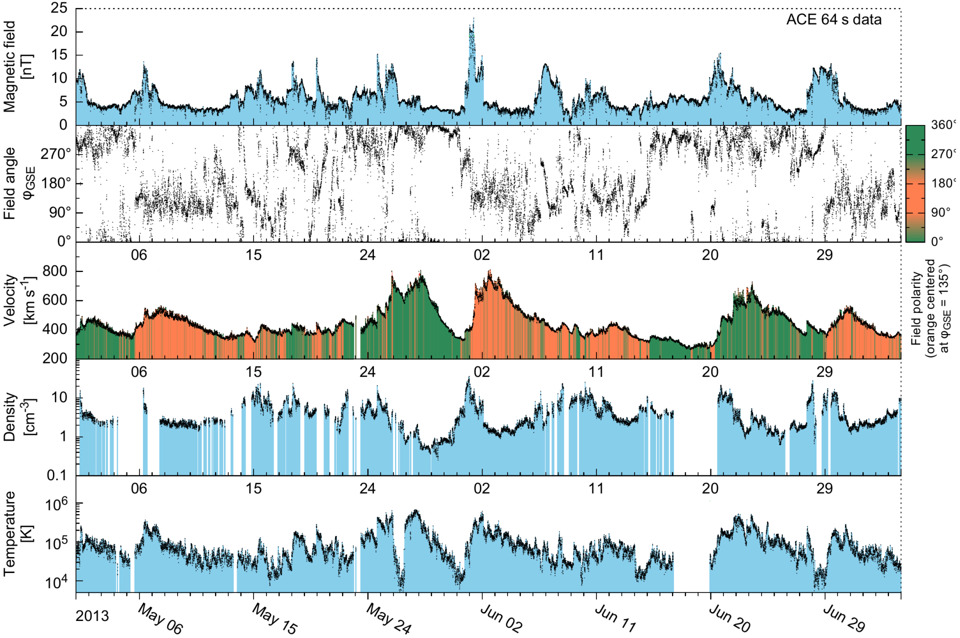
- Solar wind parameters are represented by frequency distributions instead of average values
- These are shifted with solar activity and solar distance

Solar wind data

OMNI data set (King & Papitashvili, 2005)
- intercalibrated multi-spacecraft data
- low-resolution data since 1963; high-resolution data since 1981

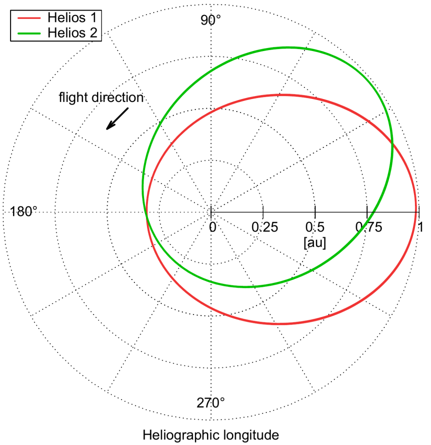


Solar wind



ACE 64 s data
Magnetic field [nT]
Field angle φGSE
Velocity [km s-1]
Density [cm-3]
Temperature [K]
Field polarity (orange centered at φGSE = 135°)
2013
May 06
May 15
May 24
Jun 02
Jun 11
Jun 20
Jun 29

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



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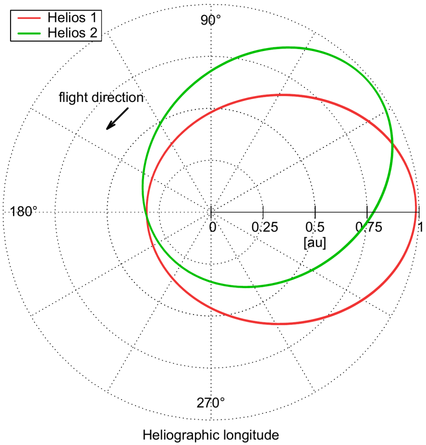
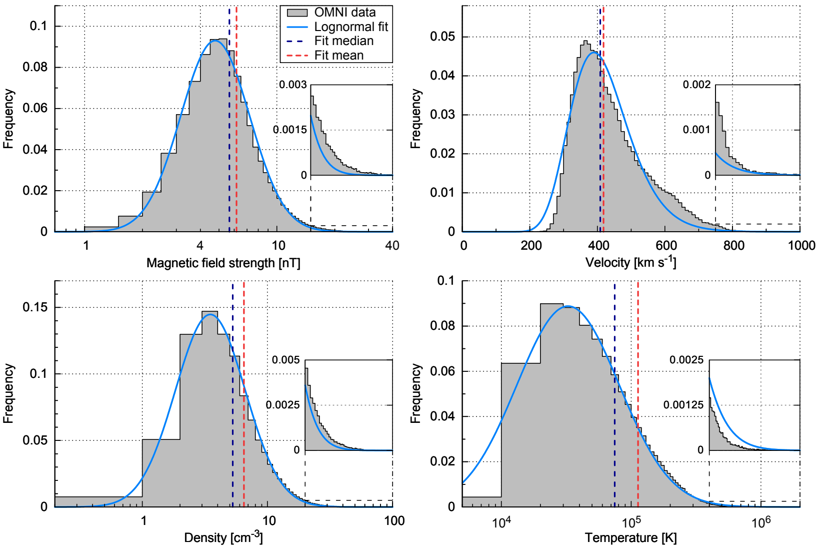


Solar wind model data use

- 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)

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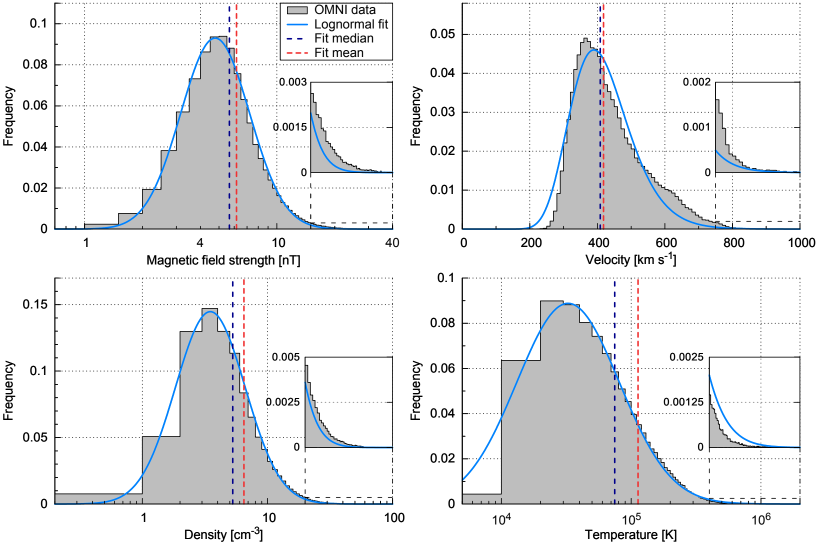

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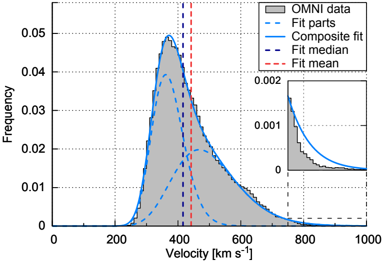
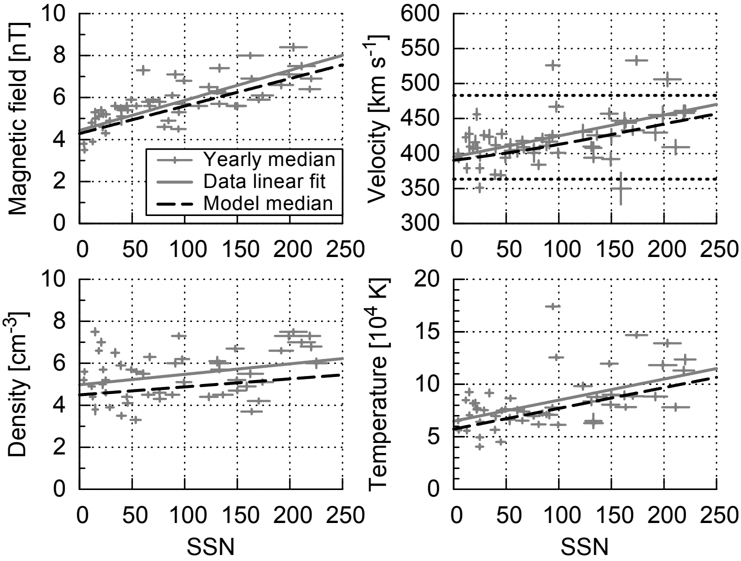


Credit: Venzmer & Bothmer (2018)

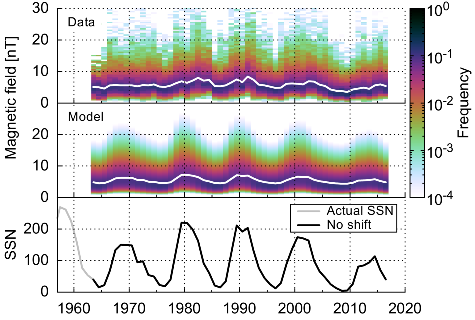
Note: Lognormal functions are fully described by their median and mean values

Linear relations with the SSN:



Credit: Venzmer & Bothmer (2018)

Solar activity dependence – OMNI data



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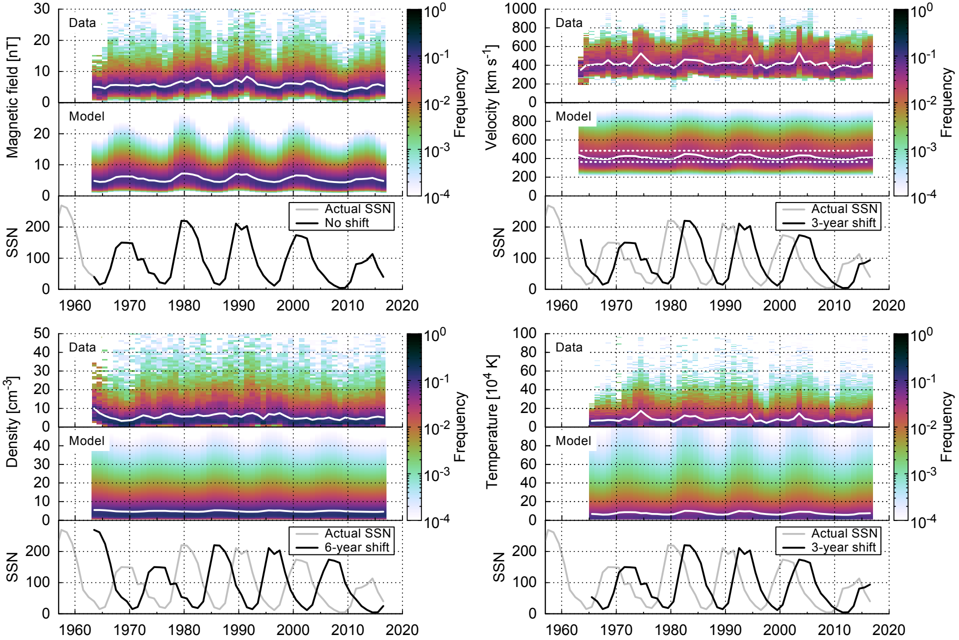
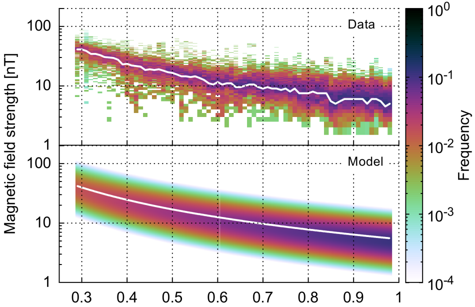


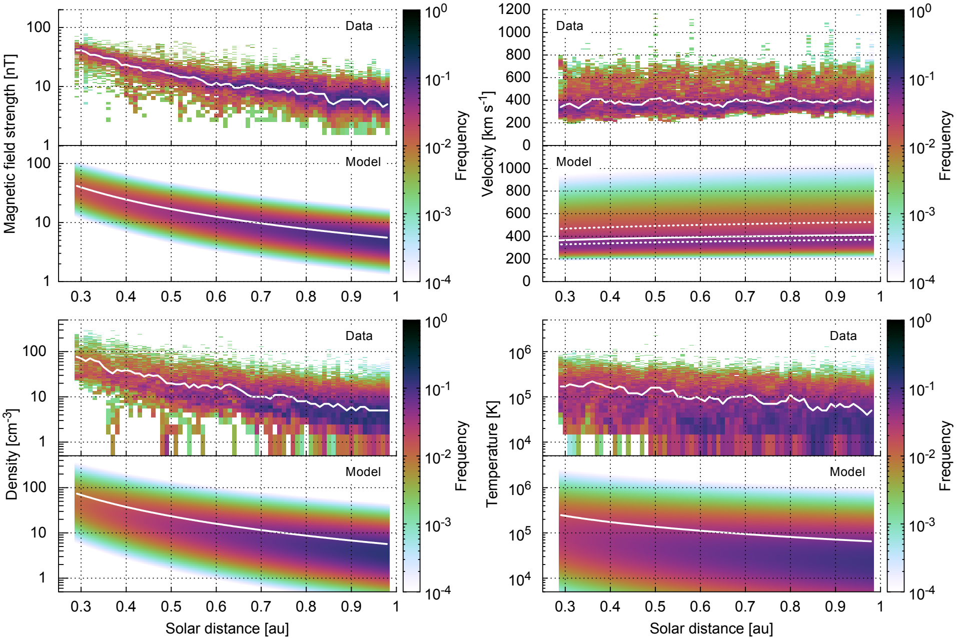
Credit: Venzmer & Bothmer (2018)

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 $ssn(t + t_{\text{lag}}), r(t)$

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Relations for the median and mean values

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

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

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

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

Density

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

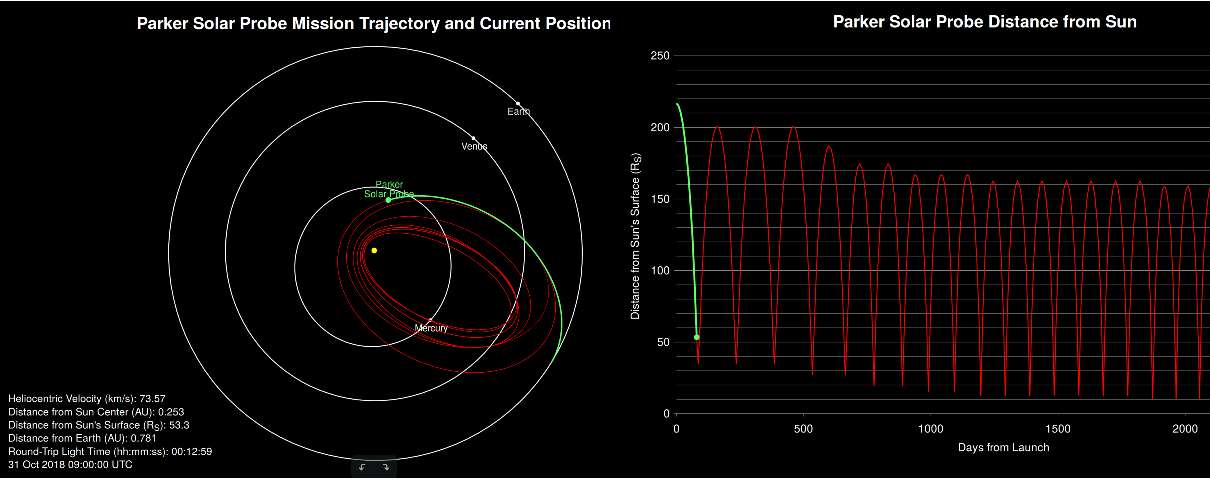
$$n_{\text{avg}}(ssn, r) = 1.305 \cdot n_{\text{med}}(ssn, r)$$

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



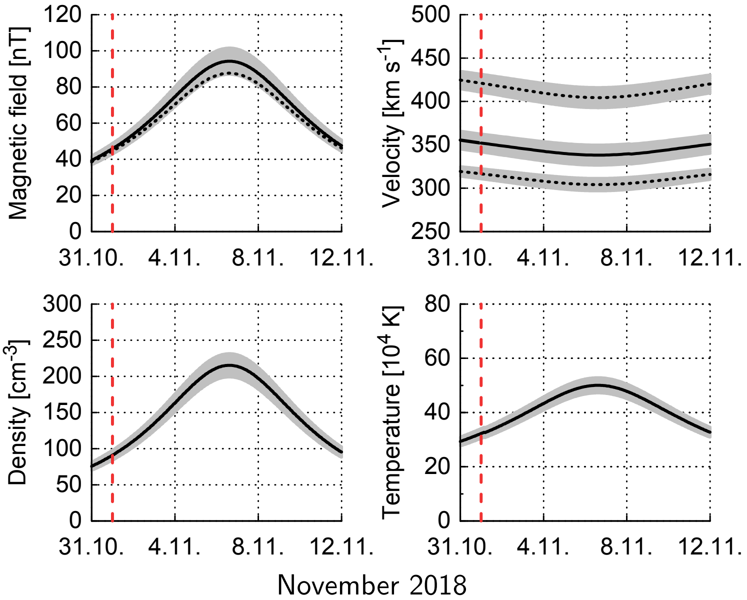
Credit: NASA

⇒ Extrapolate the model in distance

⇒ Feed the model with SSN predictions

Prediction for PSP orbit

Perihelion #1 at 36.7 $R_\odot$



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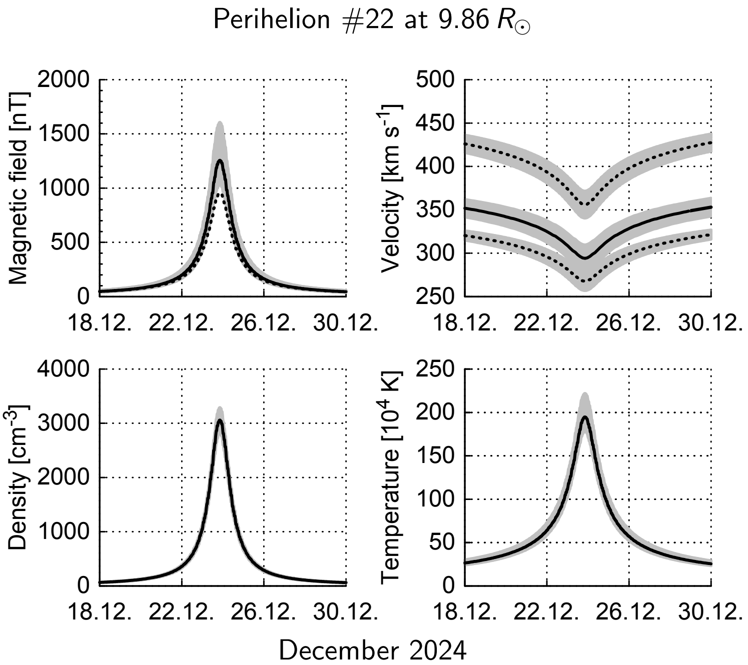

Comparison with other studies

Predicted values at 9.86 $R_\odot$

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

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- Remote observations reveal slow solar wind with velocities of 200 km s^{-1} at 10 $R_\odot$ (Sheeley et al., 1997; Wang et al., 2000)

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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

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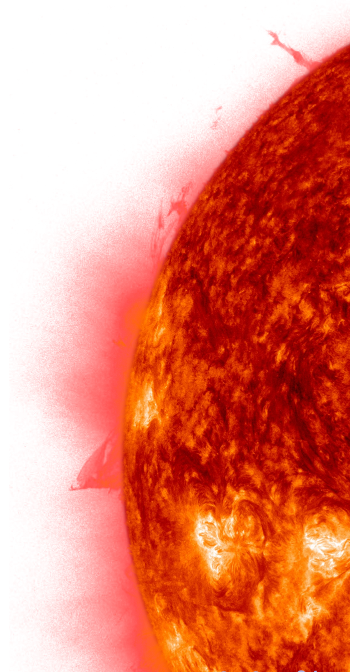
The major part of this study is published in Venzmer & Bothmer (2018)

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

Outlook

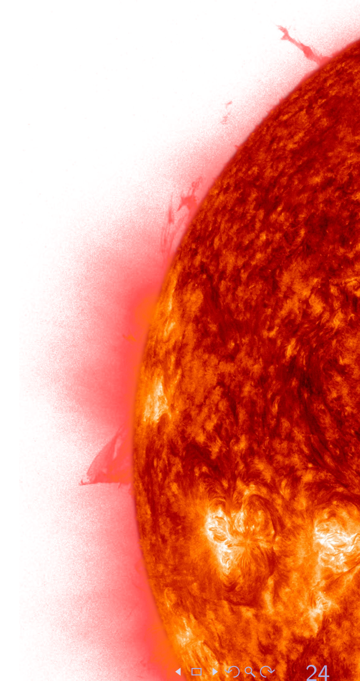
- Possible modifications to model (e.g., flux conservation)
- Refine model with additional solar wind data from Mercury probes and the upcoming Solar Orbiter mission
- The predictions can be used as a reference for the first measurements made by PSP
- The PSP measurements can be used to validate the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



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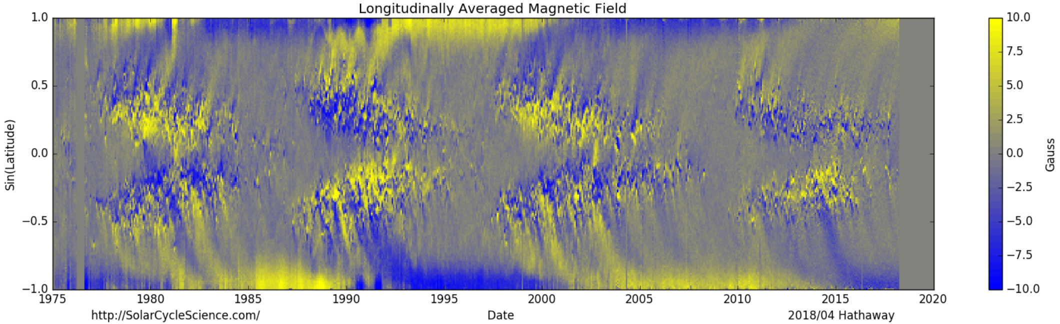
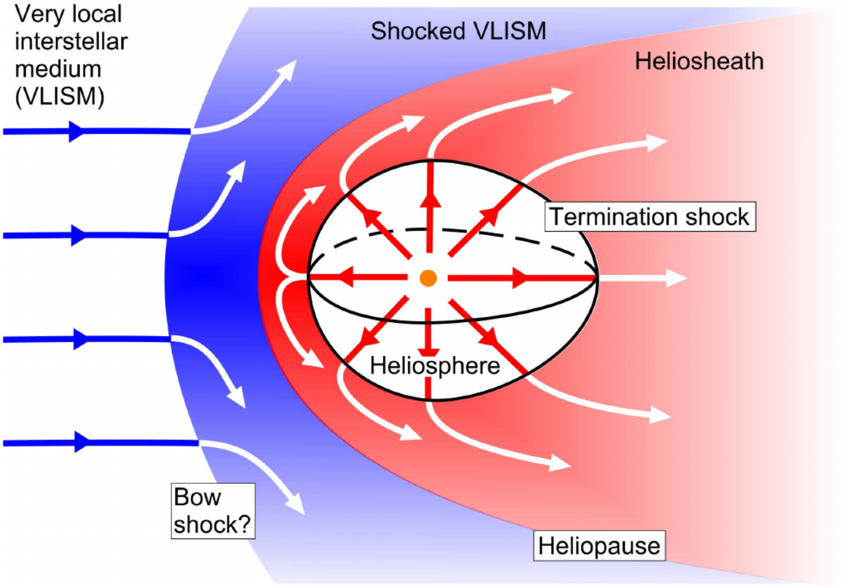
Solar activity

Magnetic butterfly diagram



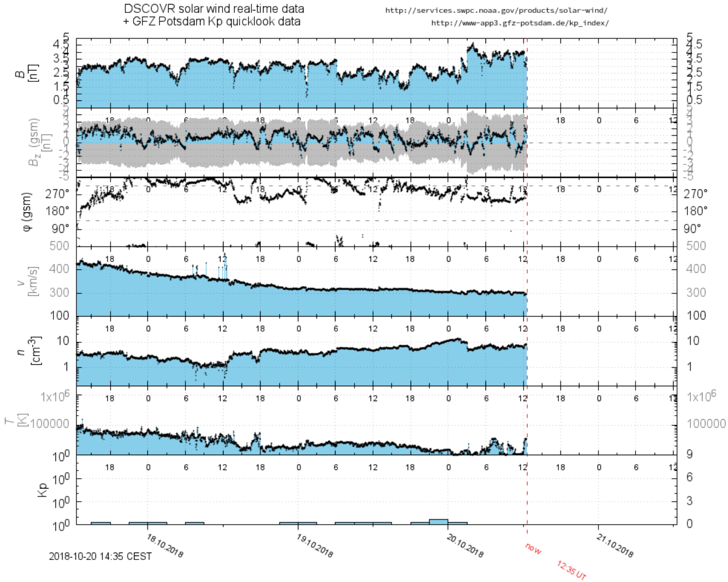
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

Solar wind



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

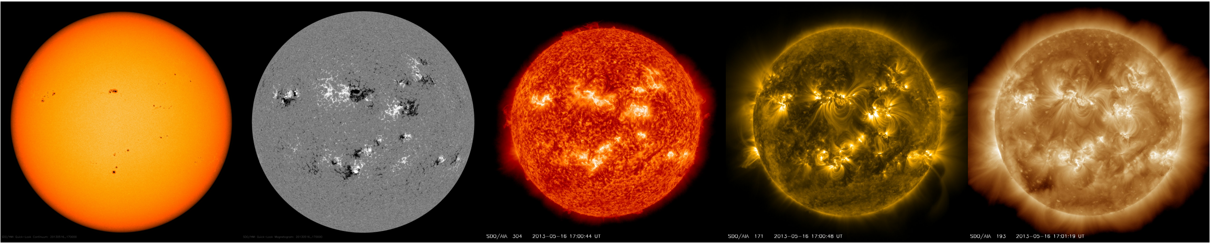
Solar wind



DSCOVR solar wind real-time data
+ GFZ Potsdam Kp quicklook data
http://services.swpc.noaa.gov/products/solar-wind/
http://www-app3.gfz-potsdam.de/kp_index/
B [nT]
Bz (gsm) [nT]
φ (gsm)
v [km/s]
n [cm-3]
T [K]
Kp
18.10.2018
19.10.2018
20.10.2018
21.10.2018
now
12:35 UT
2018-10-20 14:35 CEST

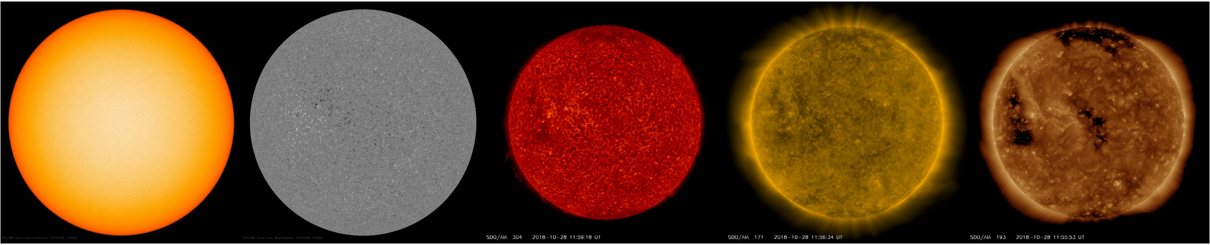
Solar surface and atmosphere

Intensitygram | Magnetogram | 304 Å | 171 Å | 193 Å



Credit: NASA SDO/HMI, 16 May 2013

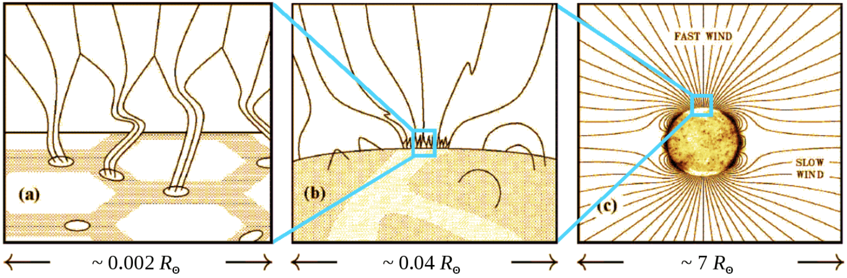
Credit: NASA SDO/AIA, 16 May 2013



Credit: NASA SDO/HMI, 28 Oct ober 2018

Credit: NASA SDO/AIA, 28 October 2018

Solar magnetic field

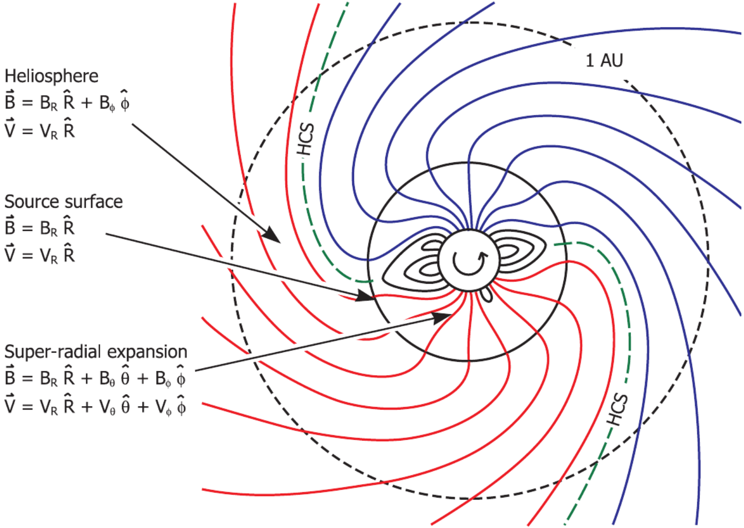


Courtesy of S. R. Cranmer

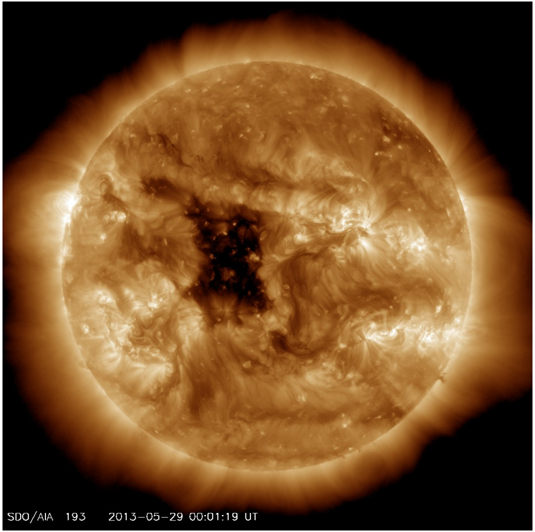
Solar magnetic field

Theoretical model (Parker, 1958)

- Expanding isothermal solar atmosphere
- Parker spiral field geometry

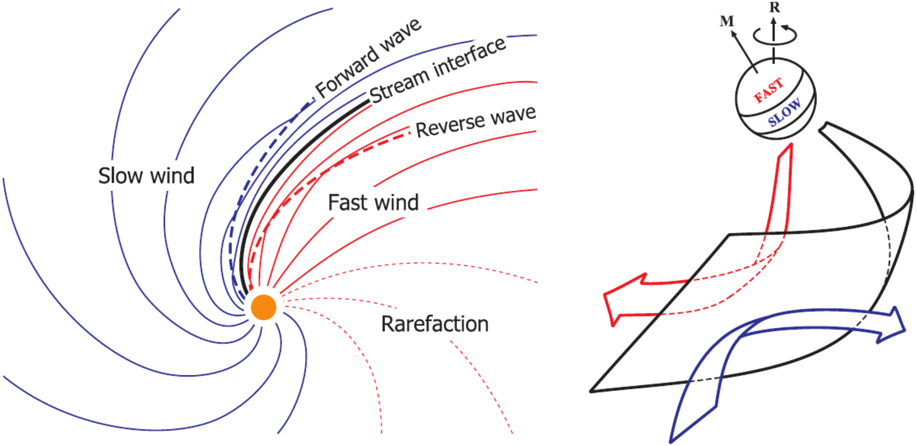


Slow and fast solar wind



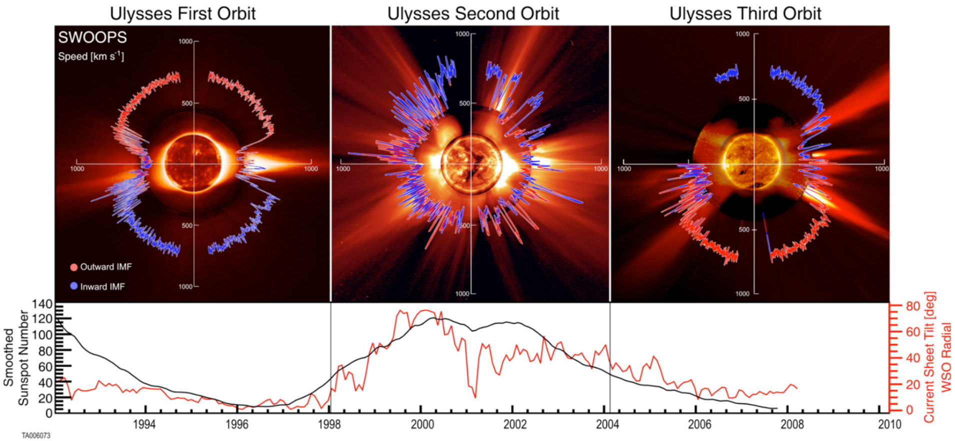
Credit: NASA/SDO and the AIA, EVE and HMI science teams

Slow and fast solar wind



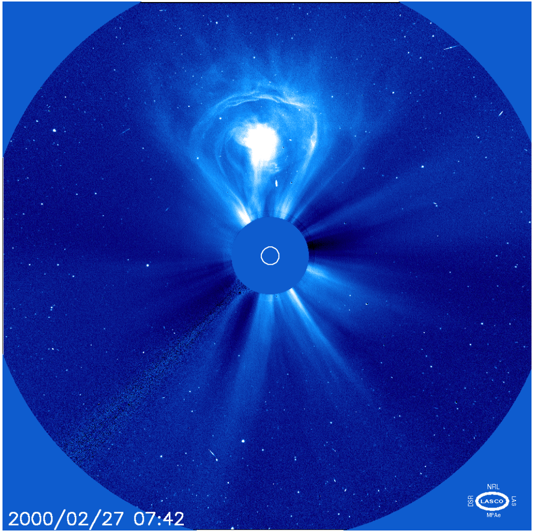
Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

Solar activity



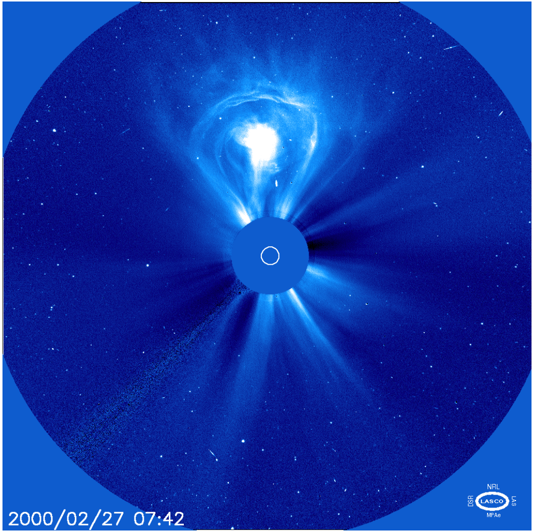
Credit: McComas et al. (2008a, Fig. 1)

Coronal mass ejections

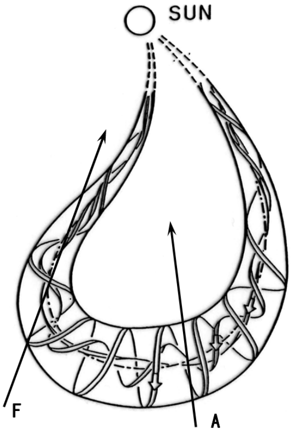


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

Coronal mass ejections

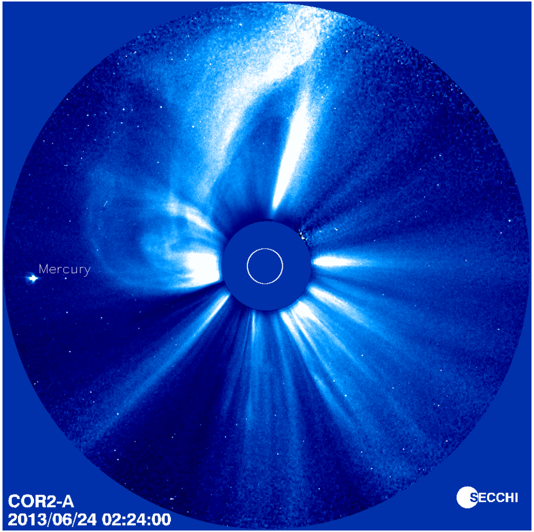


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

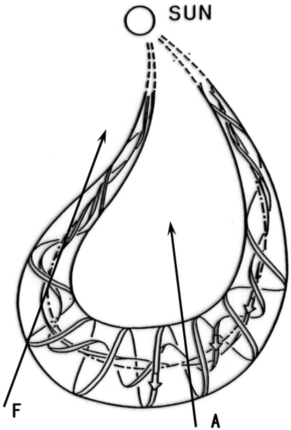


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections

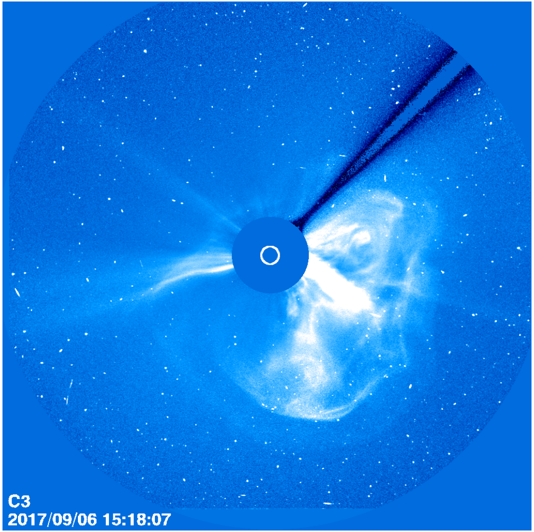


Courtesy of STEREO/COR2 consortium (NASA)

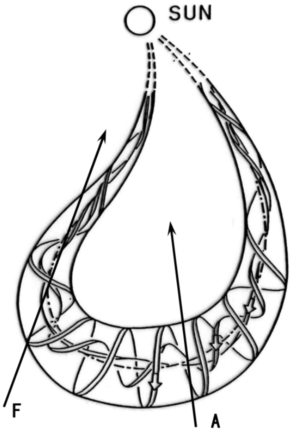


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections

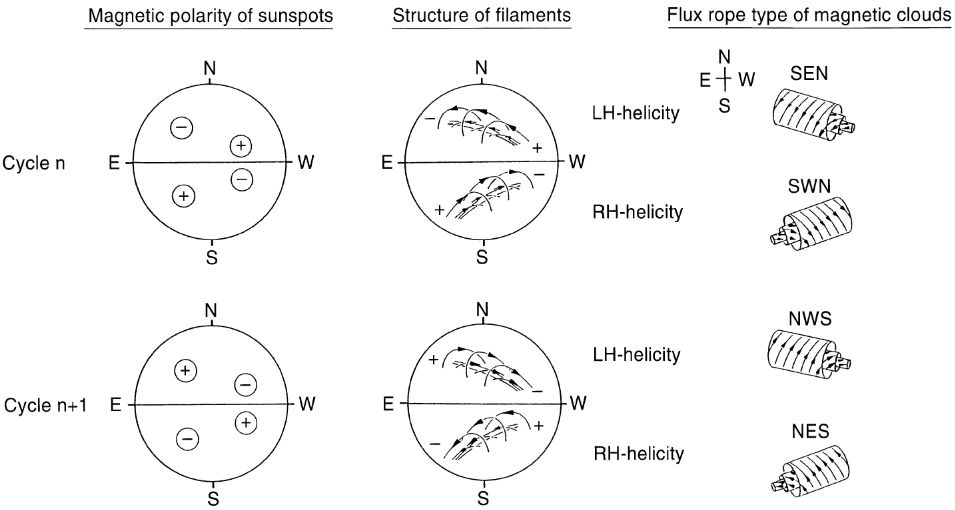


Courtesy of SOHO/LASCO consortium; SOHO is a project of international cooperation between ESA and NASA



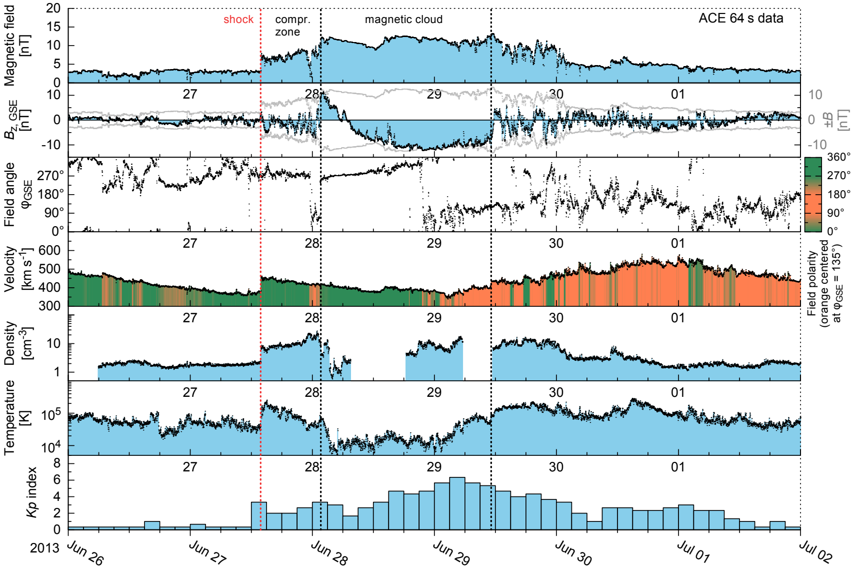
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

CME orientation



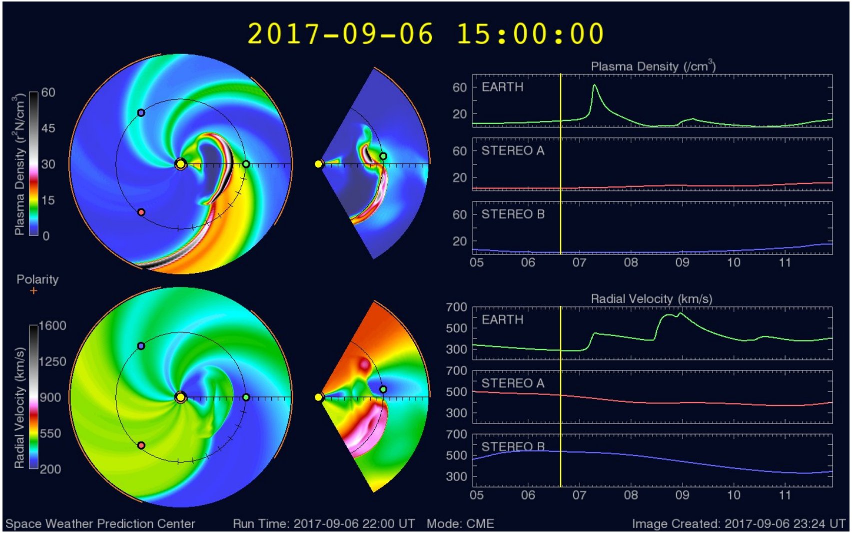
Credit: Bothmer & Schwenn (1998, Fig. 18)

In-situ CMEs



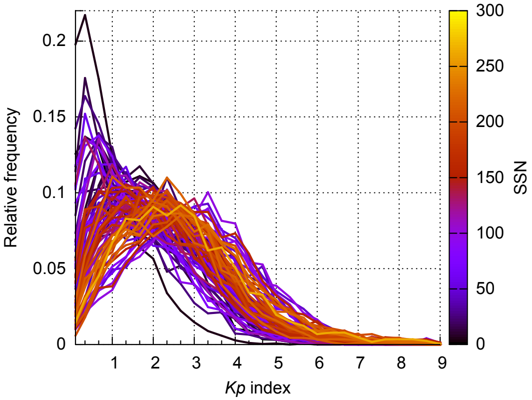
shock
compr. zone
magnetic cloud
ACE 64 s data
Magnetic field [nT]
$B_{z, GSE}$ [nT]
±B [nT]
Field angle φ_{GSE}
Velocity [km s^{-1}]
Field polarity (orange centered at φ_{GSE} = 135°)
Density [cm^{-3}]
Temperature [K]
Kp index
2013
Jun 26
Jun 27
Jun 28
Jun 29
Jun 30
Jul 01
Jul 02

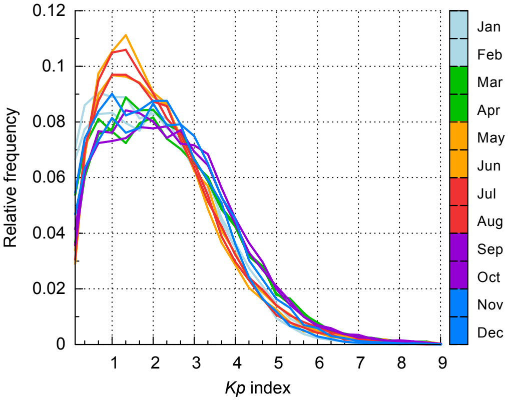
Solar wind and CME forecast



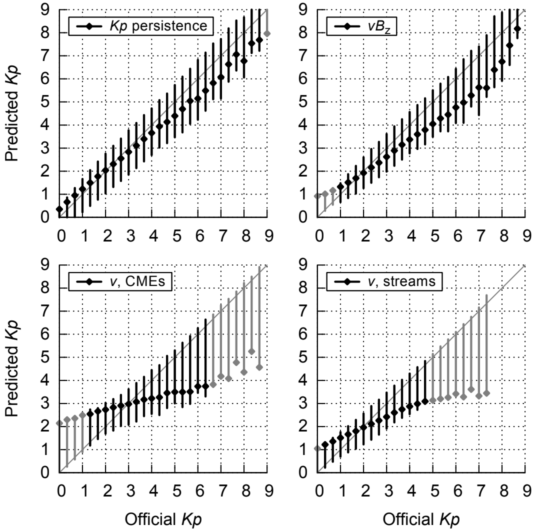
Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

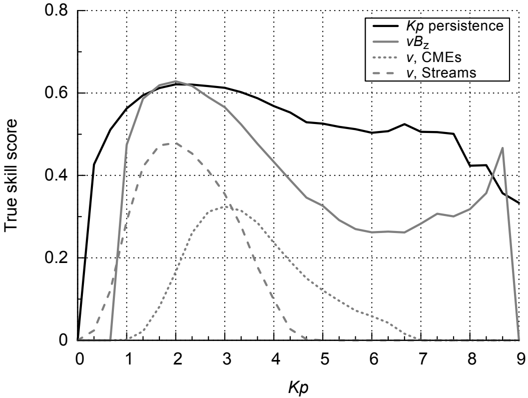
Kp long-term variations



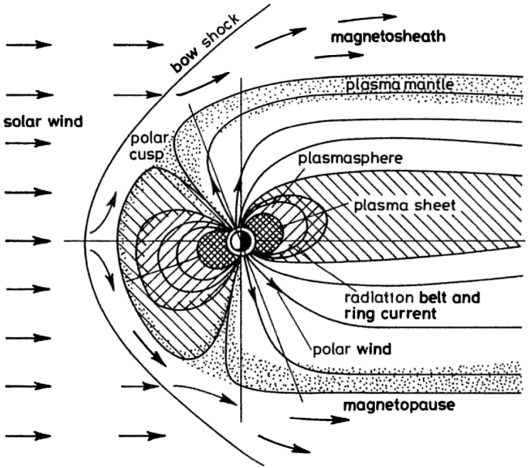


Prediction performance





Magnetosphere

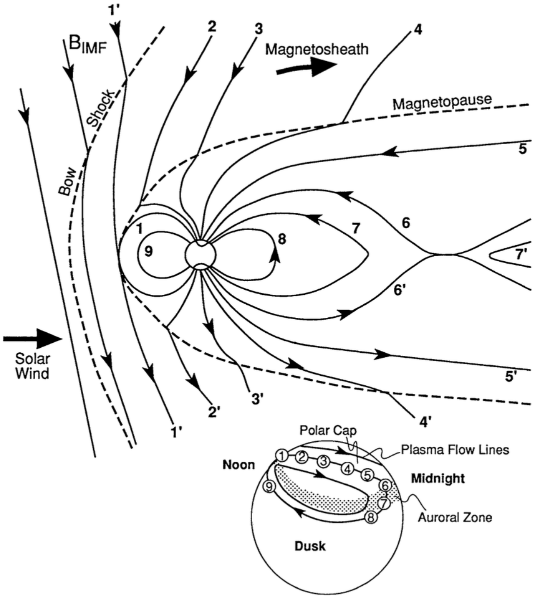


Credit: Davies (1990, Fig. 2.12)

Interaction mechanisms between solar wind and magnetosphere:

- Reconnection
- Turbulence
- Compression
- Induction

Magnetosphere



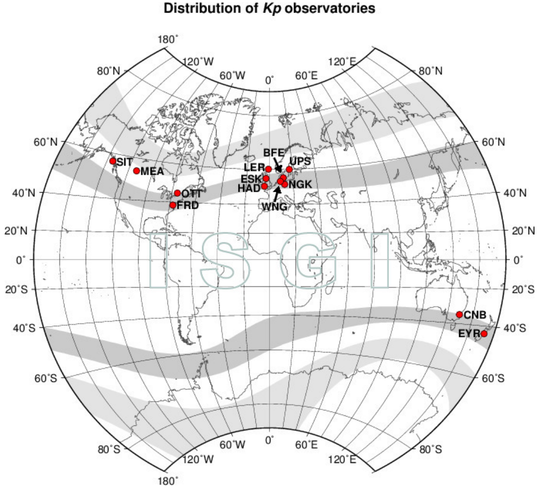
Credit: Hughes (1995, Fig. 9.11)

Factors that influence the reconnection flux rate:

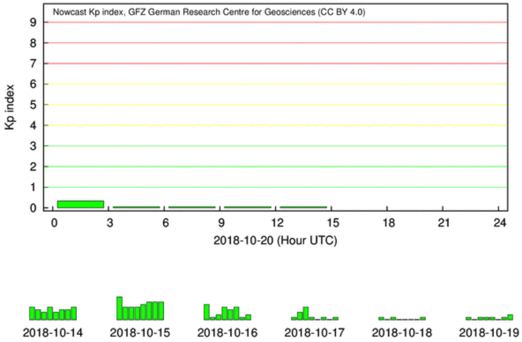
- Velocity
- Magnetic field strength
- Magnetic field angle
- Size of reconnection region

Kp index

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

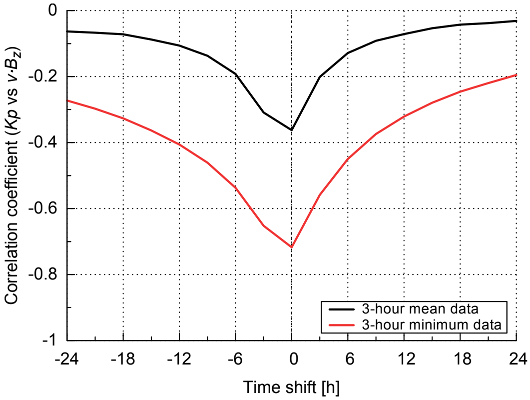


Courtesy of International Service of Geomagnetic Indices (ISGI), 2013

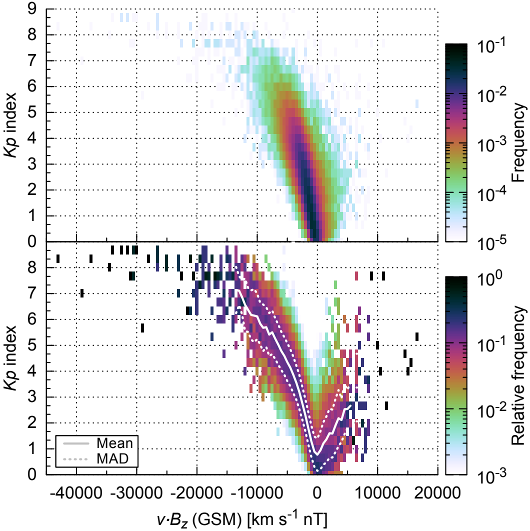


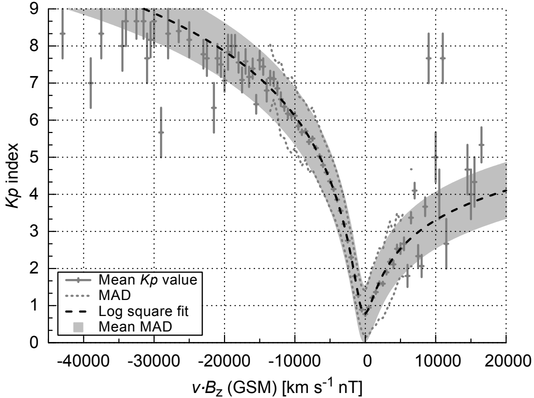
Credit: GFZ Potsdam, 2018

Solar wind electric field

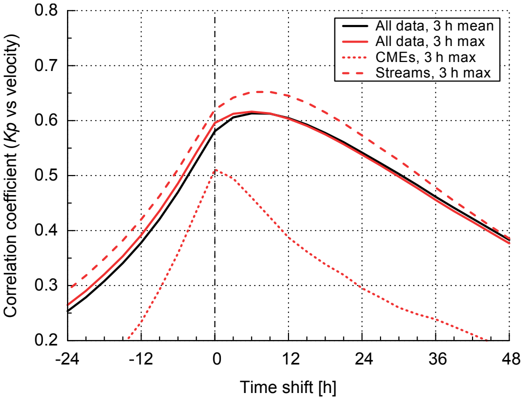


Solar wind electric field

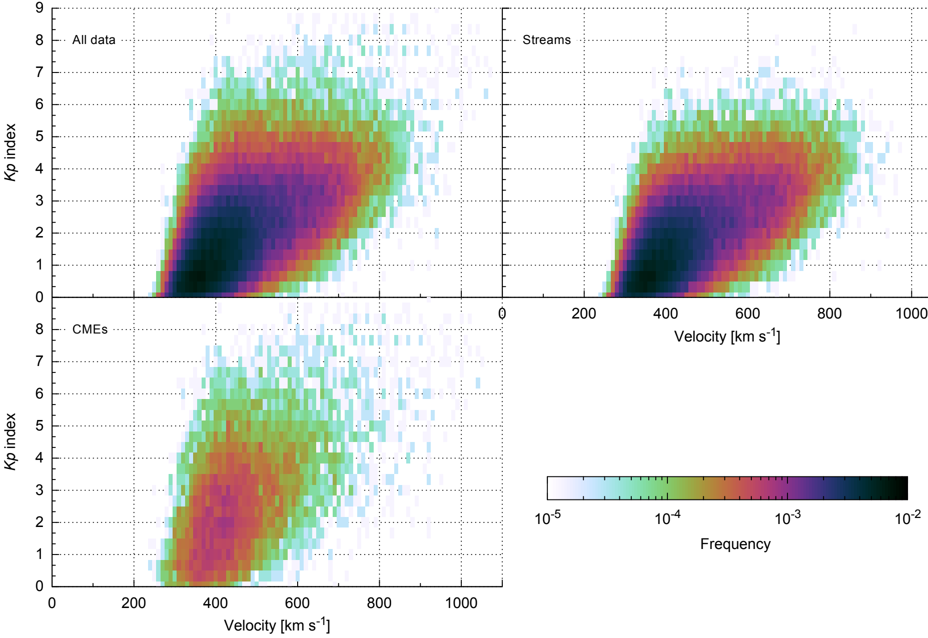


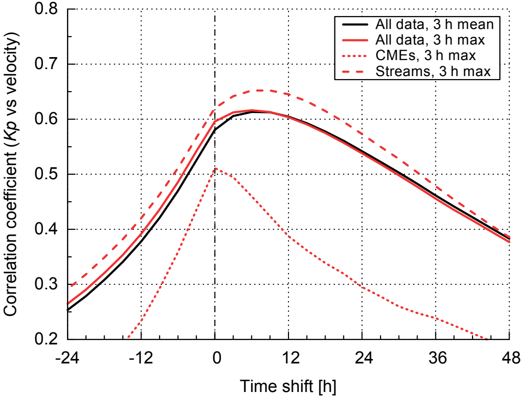


Solar wind velocity



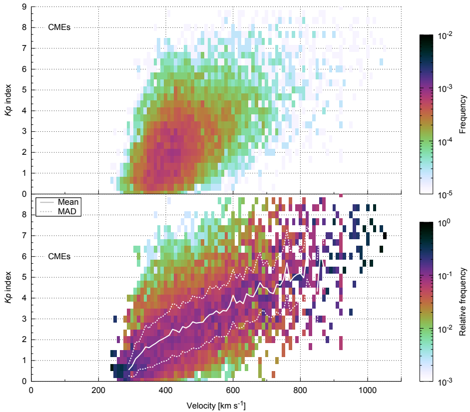
Solar wind velocity

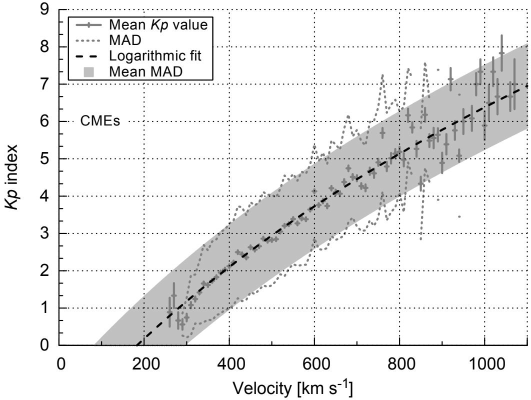




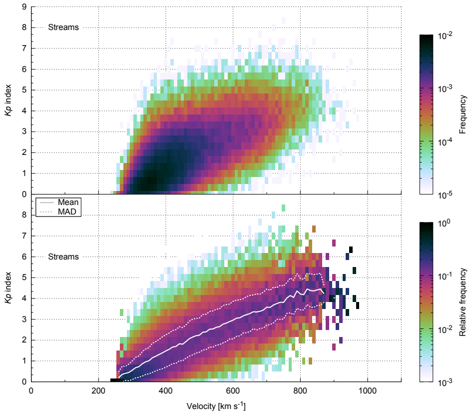
All data, 3 h mean
All data, 3 h max
CMEs, 3 h max
Streams, 3 h max
Correlation coefficient (*Kp* vs velocity)
Time shift [h]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-24
-12
0
12
24
36
48

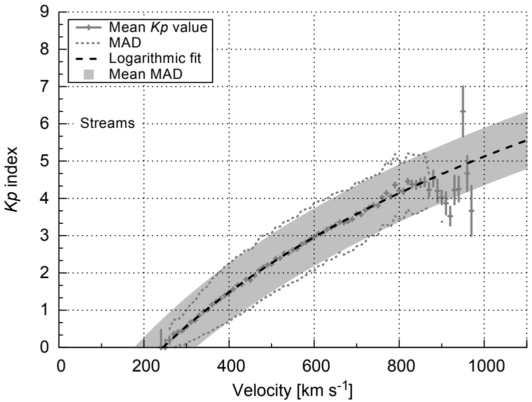
CME velocity

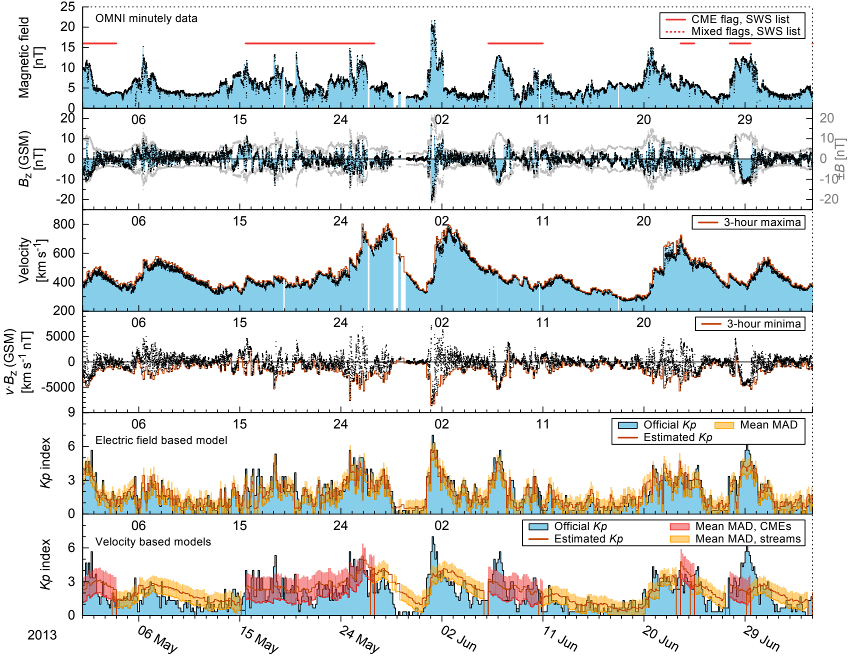




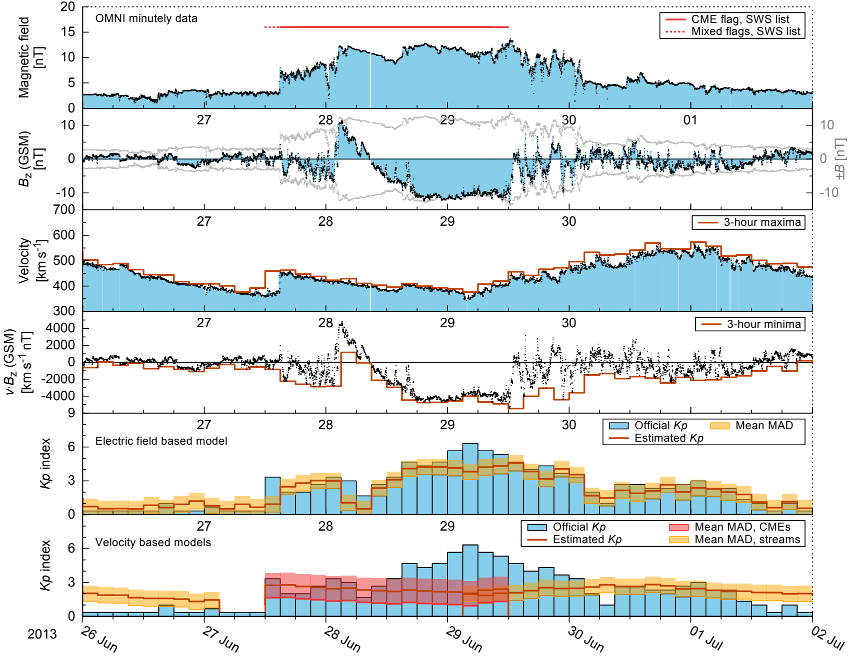
Stream velocity







OMNI minutely data
CME flag, SWS list
Mixed flags, SWS list
Magnetic field [nT]
B_z (GSM) [nT]
±B [nT]
Velocity [km s^{-1}]
3-hour maxima
$v \cdot B_z$ (GSM) [km s^{-1} nT]
3-hour minima
Electric field based model
Official Kp
Mean MAD
Estimated Kp
Kp index
Velocity based models
Mean MAD, CMEs
Mean MAD, streams
2013
06 May
15 May
24 May
02 Jun
11 Jun
20 Jun
29 Jun



OMNI minutely data
CME flag, SWS list
Mixed flags, SWS list
Magnetic field [nT]
B_Z (GSM) [nT]
±B [nT]
Velocity [km s^{-1}]
3-hour maxima
$v \cdot B_Z$ (GSM) [km s^{-1} nT]
3-hour minima
Electric field based model
Official Kp
Mean MAD
Estimated Kp
Kp index
Velocity based models
Official Kp
Estimated Kp
Mean MAD, CMEs
Mean MAD, streams
2013
26 Jun
27 Jun
28 Jun
29 Jun
30 Jun
01 Jul
02 Jul

Results

Predictive Kp models based on relations with

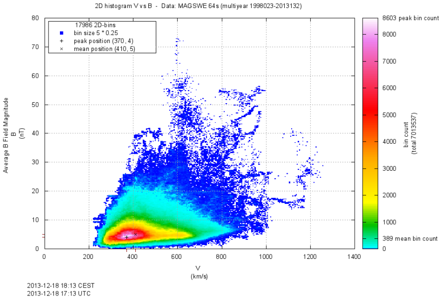
- Solar wind electric field proxy (vB_z)
- Velocity of CME-associated flows (v_{CME})
- Velocity of solar wind streams (v_{stream})

Conclusions

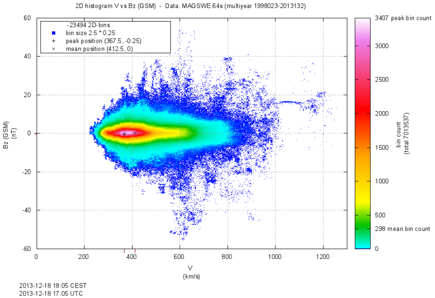
- The processing of 3-hour extrema of high time resolution data captures short-term geoeffective magnetic features that are neglected when averaging over 3-hour intervals
- The isolated treatment of CMEs and streams is beneficial to the prediction accuracy of Kp
- The prediction models perform well for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

Prediction performance

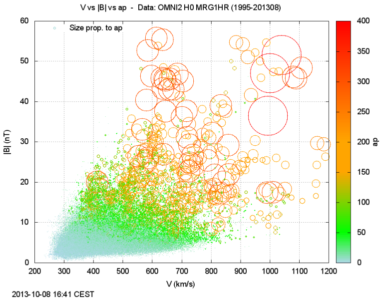
Solar wind



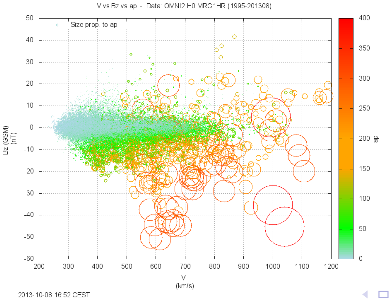
2D histogram V vs B - Data: MAGSWE 64s (multiyear 1998023-2013132)
17986 2D-bins
bin size 5 * 0.25
peak position (370, 4)
mean position (410, 5)
8603 peak bin count
389 mean bin count
bin count
(total 7013537)
Average B Field Magnitude
B
(nT)
V
(km/s)
2013-12-18 18:13 CEST
2013-12-18 17:13 UTC



2D histogram V vs Bz (GSM) - Data: MAGSWE 64s (multiyear 1998023-2013132)
-23494 2D-bins
bin size 2.5 * 0.25
peak position (367.5, -0.25)
mean position (412.5, 0)
3407 peak bin count
298 mean bin count
bin count
(total 7013537)
Bz (GSM)
(nT)
V
(km/s)
2013-12-18 18:05 CEST
2013-12-18 17:05 UTC

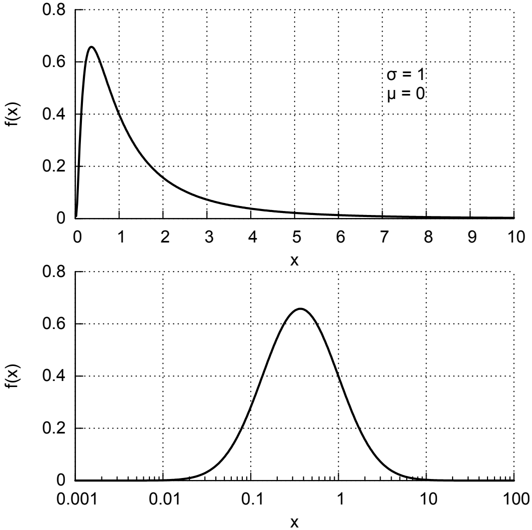


V vs |B| vs ap - Data: OMNI2 H0 MRG1HR (1995-201308)
Size prop. to ap
|B| (nT)
V (km/s)
ap
2013-10-08 16:41 CEST



V vs Bz vs ap - Data: OMNI2 H0 MRG1HR (1995-201308)
Size prop. to ap
Bz (GSM)
(nT)
V
(km/s)
ap
2013-10-08 16:52 CEST

Lognormal distribution



Probability density function:

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

Location (μ) and shape parameter (σ).

Median and average:

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

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

Near-Sun region

Unsolved problems:

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

Parker Solar Probe

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

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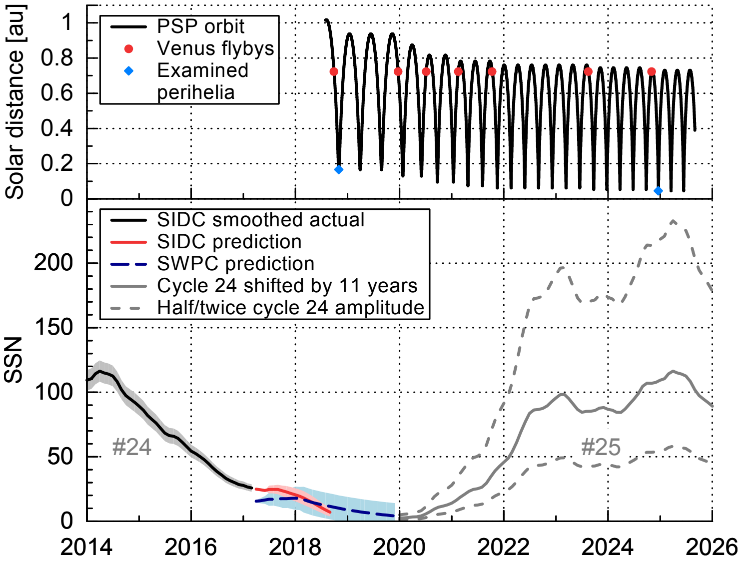
Scientific instruments

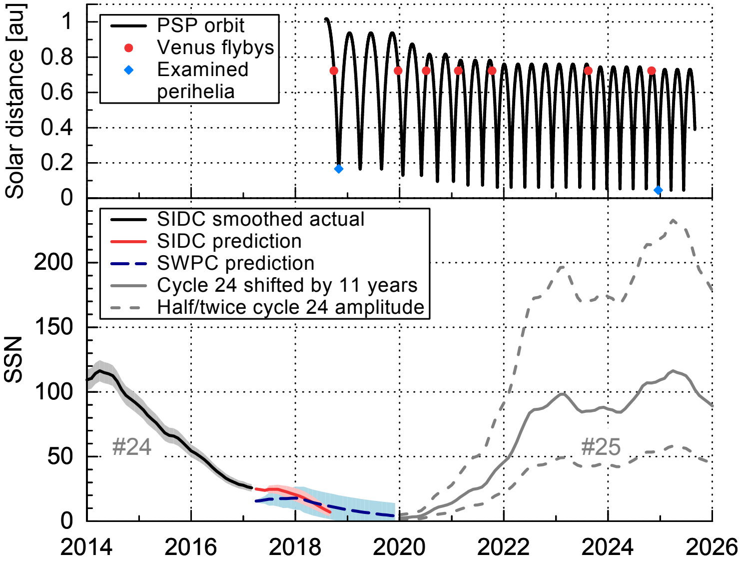
- FIELDS – Electromagnetic Fields Investigation
- IS$\odot$IS – Integrated Science Investigation of the Sun
- SWEAP – Solar Wind Electrons Alphas and Protons Investigation
- WISPR – Wide-Field Imager for Solar Probe

PSP distance and solar activity



Credit: Venzmer & Bothmer (2018)

PSP distance and solar activity



Credit: Venzmer & Bothmer (2018)

Perihelion #1
2018: solar minimum

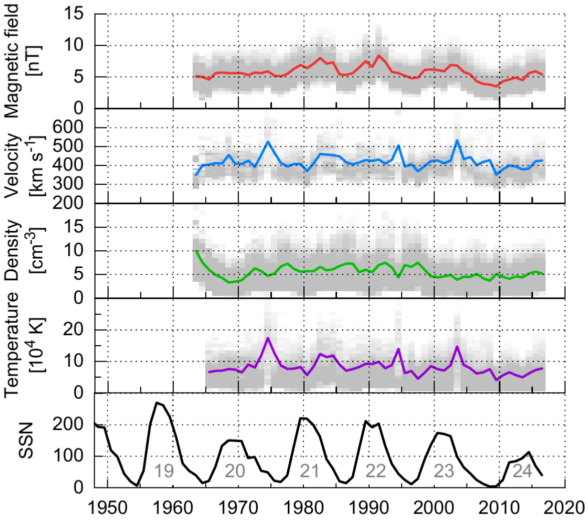
Perihelion #22
2024: solar maximum

⇒ Predictive models have to be dependent on

- solar distance
- solar activity (SSN)

Solar activity dependence – OMNI data

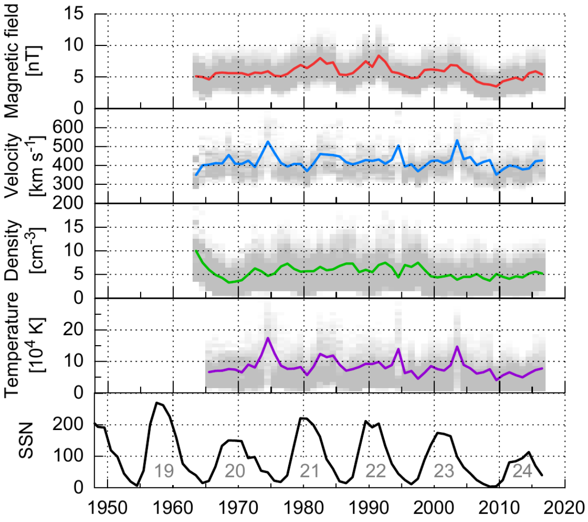
Yearly median values:



Credit: Venzmer & Bothmer (2018)

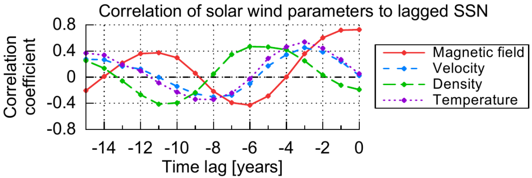
Solar activity dependence – OMNI data

Yearly median values:



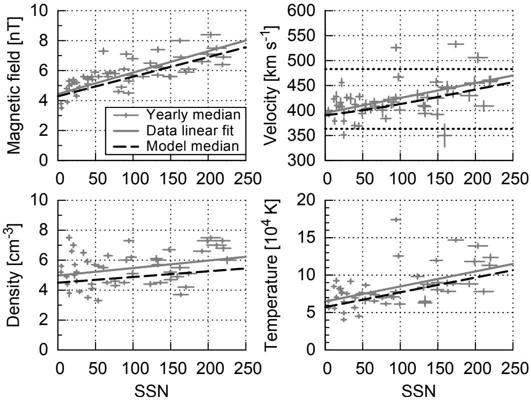
Credit: Venzmer & Bothmer (2018)

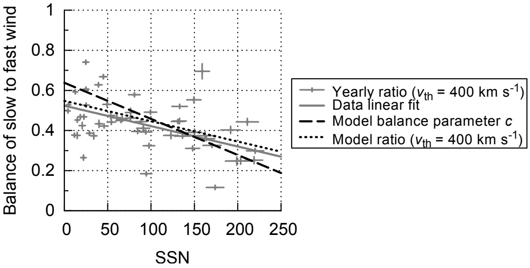
Find time lag with highest correlation coefficient:



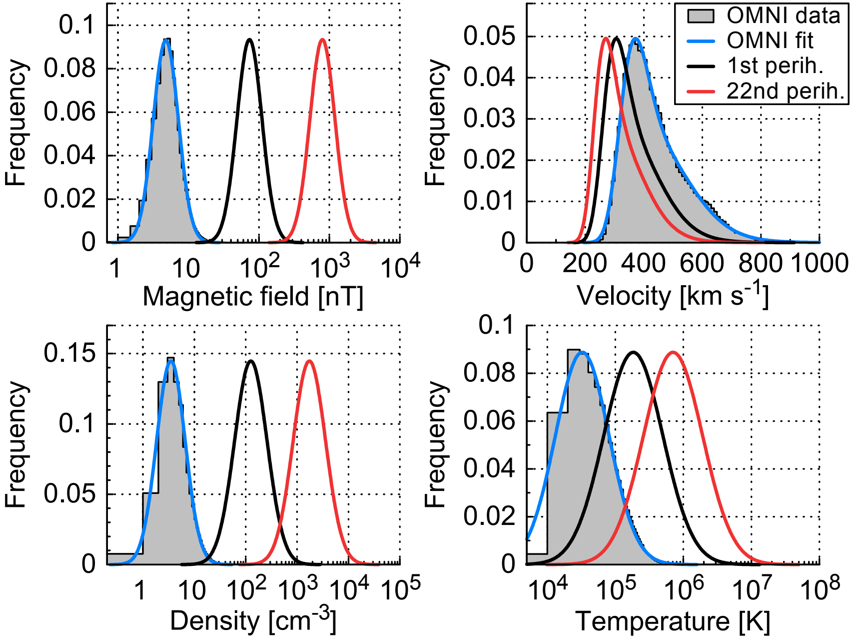
Credit: Venzmer & Bothmer (2018)

Solar activity

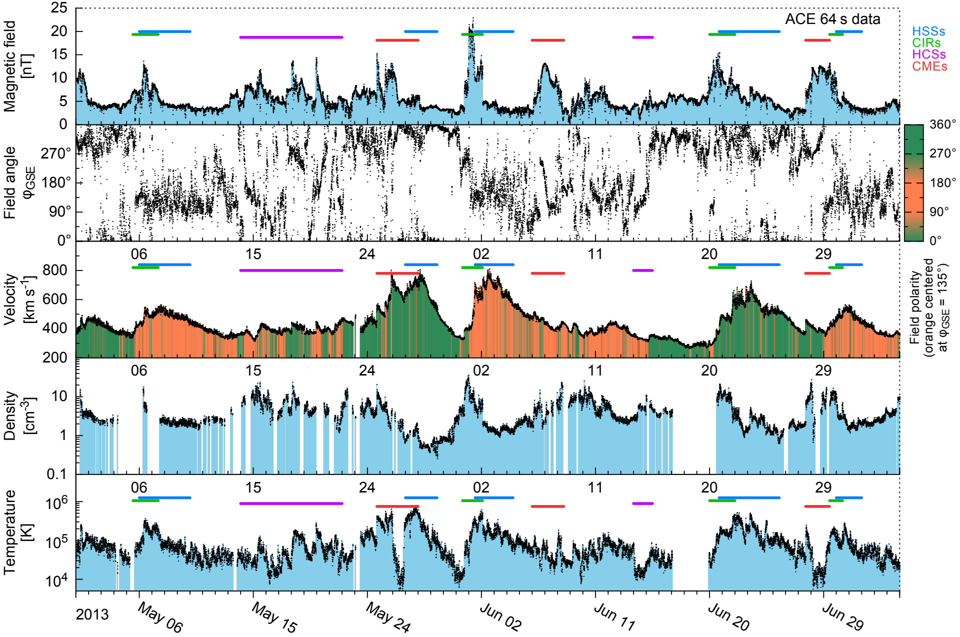




PSP perihelia prediction



Solar wind



ACE 64 s data
HSSs
CIRs
HCSs
CMEs
Magnetic field [nT]
Field angle φ_{GSE}
Velocity [km s^{-1}]
Density [cm^{-3}]
Temperature [K]
Field polarity (orange centered at φ_{GSE} = 135°)
360°
270°
180°
90°
0°
06
15
24
02
11
20
29
2013
May 06
May 15
May 24
Jun 02
Jun 11
Jun 20
Jun 29