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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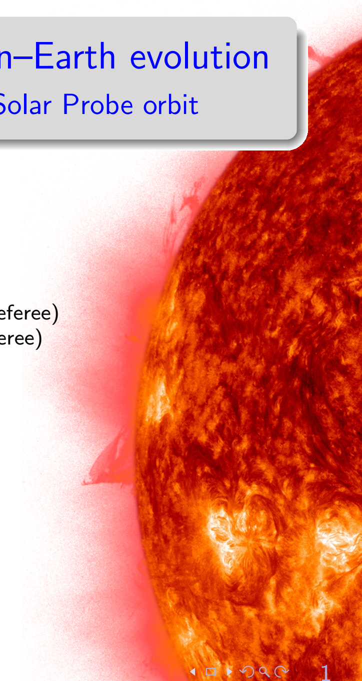

The two studies in my thesis

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Geomagnetic impact of the solar wind

I derived relations to predict geomagnetic activity from

- Solar wind electric field
- Velocity of coronal mass ejections
- Velocity of solar wind streams

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I use existing solar wind data to derive

- Solar wind model for the inner heliosphere
- Extrapolation to the near-Sun region
- Prediction for Parker Solar Probe orbit

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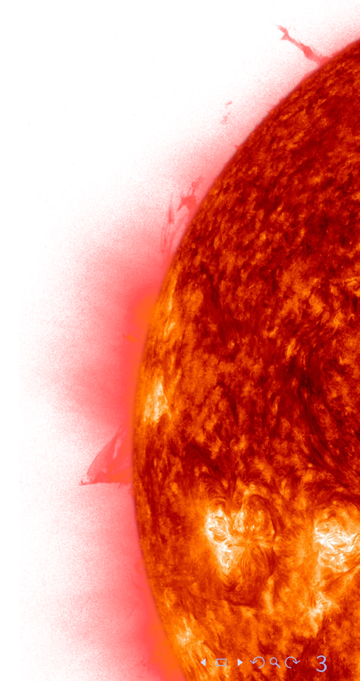
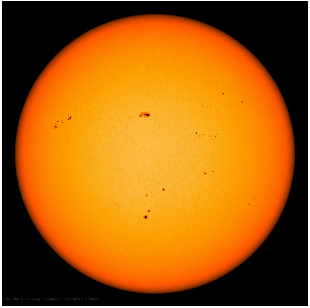
  - Solar activity
  - Solar wind
  - Parker Solar Probe (PSP)
- Empirical solar wind model
  - Solar wind model
  - Prediction for PSP orbit
- Summary



Solar activity



Credit: NASA SDO/HMI, 16 May 2013

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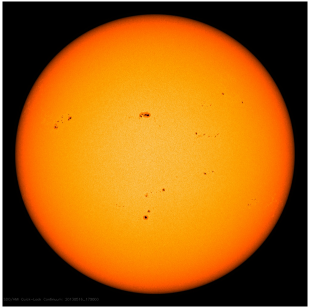

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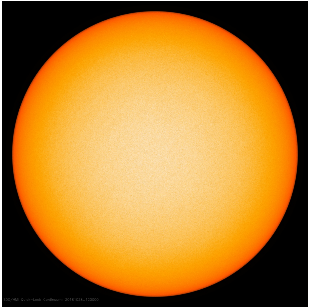
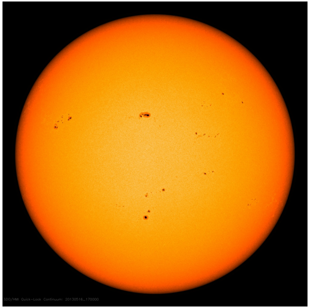


Credit: NASA SDO/HMI, 28 October 2018



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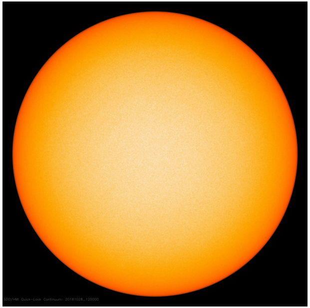

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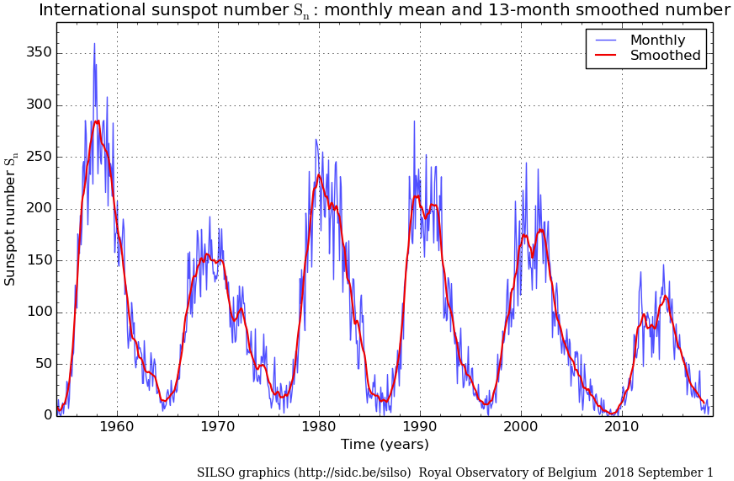
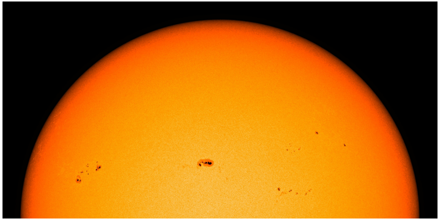
11-year sunspot number cycle



Solar activity



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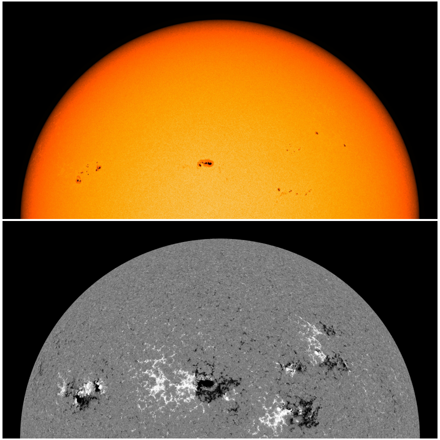

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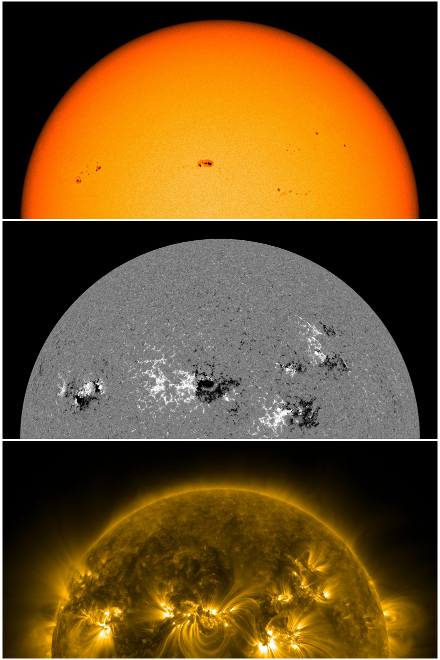

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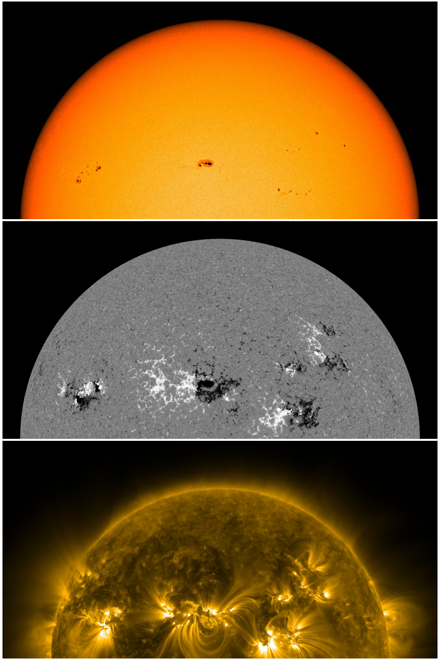

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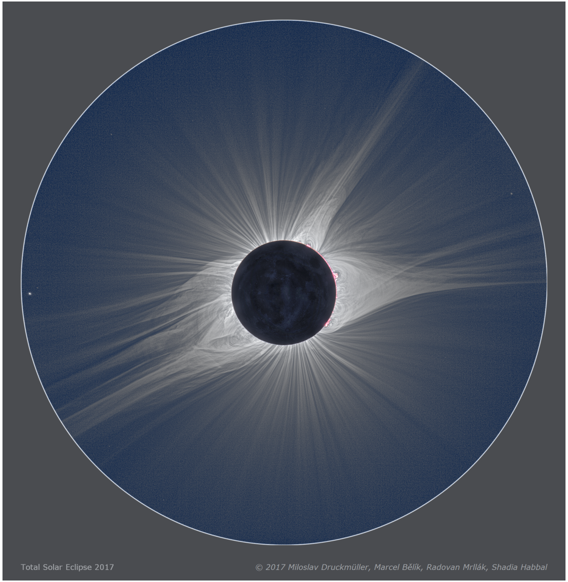

Credit: Miloslav Druckmüller, Marcel Bělík, Radovan Mrllák, Shadia Habbal, 2017

Solar wind

- Theoretical model (Parker, 1958)
  - Expanding isothermal solar atmosphere
  - Parker spiral field geometry

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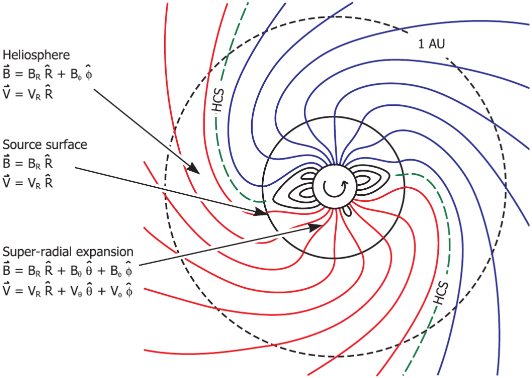
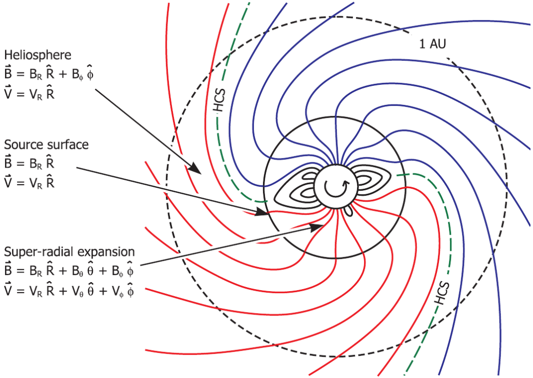


Credit: Owens & Forsyth (2013, Fig. 1), adapted from Schatten et al. (1969, Fig. 1)

Solar wind

Solar wind

- Theoretical model (Parker, 1958)
  - Expanding isothermal solar atmosphere
  - Parker spiral field geometry
- In-situ measurements confirmed its existence in 1959
- Monitored continuously near Earth since



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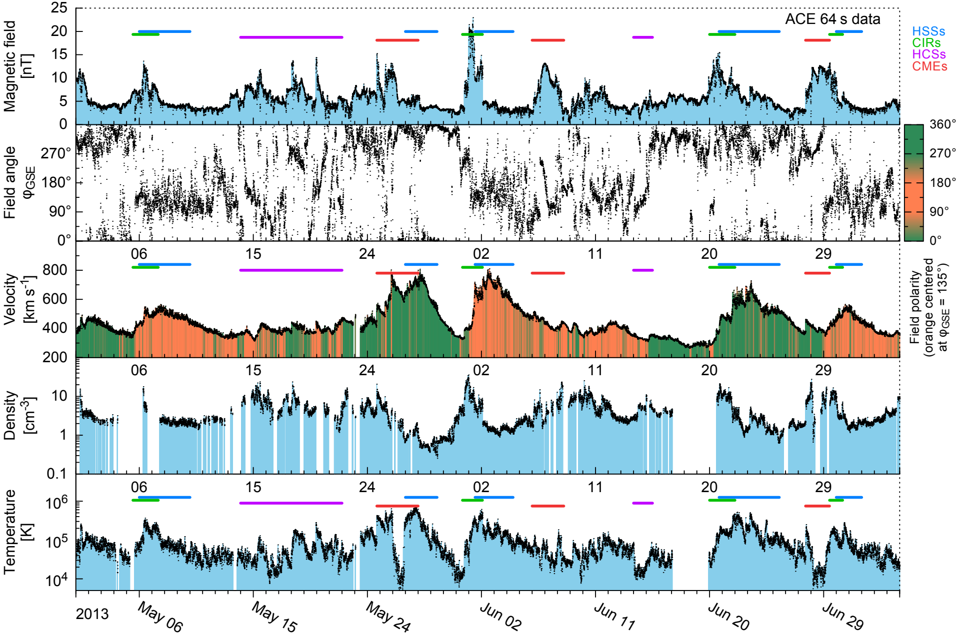
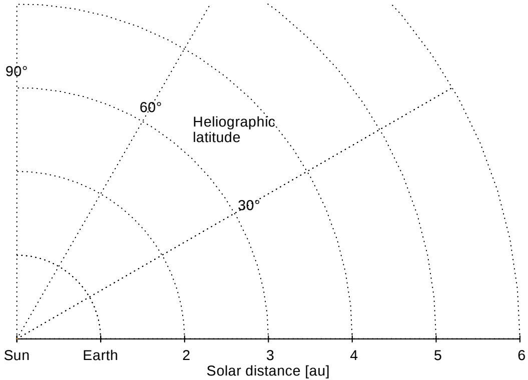


ACE 64 s data
HSSs
CIRs
HCSs
CMEs
Magnetic field [nT]
Field angle φGSE
Velocity [km s-1]
Density [cm-3]
Temperature [K]
Field polarity (orange centered at φGSE = 135°)
360°
270°
180°
90°
0°
06
15
24
02
11
20
29
2013
May 06
May 15
May 24
Jun 02
Jun 11
Jun 20
Jun 29

Measured in-situ throughout the heliosphere:



Measured in-situ throughout the heliosphere:

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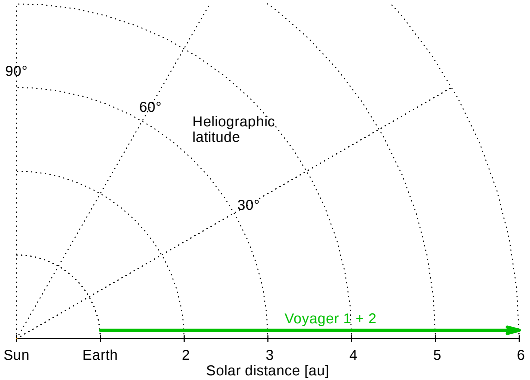
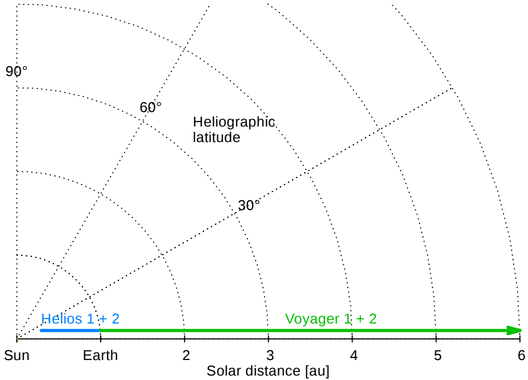


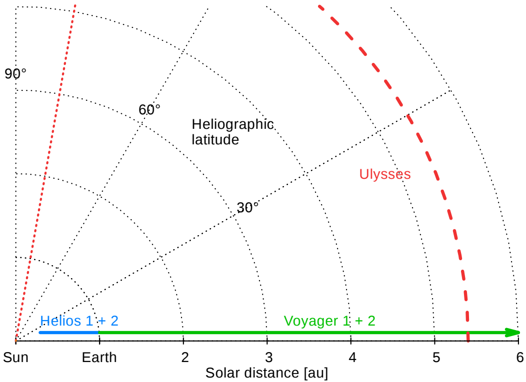
Measured in-situ throughout the heliosphere:

- Voyager 1 & 2 – out to heliopause (1–120 au)
- Helios 1 & 2 – down to Mercury (0.29–0.98 au)



Measured in-situ throughout the heliosphere:

- Voyager 1 & 2 – out to heliopause (1–120 au)
- Helios 1 & 2 – down to Mercury (0.29–0.98 au)
- Ulysses – up to high heliolatitudes ($\pm 79^\circ$)



Solar wind

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

The near-Sun region is of special scientific interest:

- Coronal heating problem
- Solar wind acceleration

Parker Solar Probe

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

Primary 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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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

Parker Solar Probe

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

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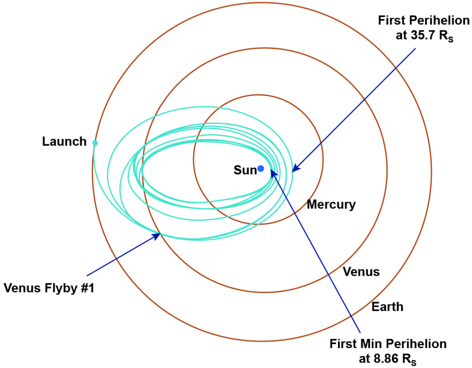

Credit: NASA/Johns Hopkins APL, 2018

Parker Solar Probe

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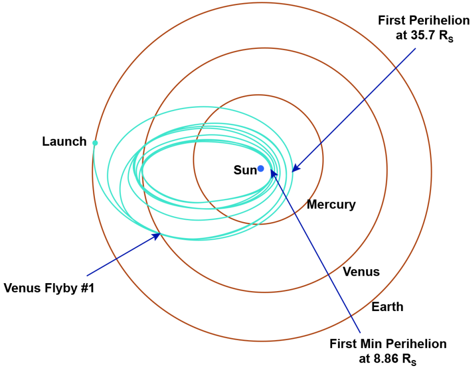

Credit: NASA/Johns Hopkins APL, 2018

Launch	12 August 2018
1st Venus flyby	3 October
Sun-closest spacecraft ever	29 October
1st perihelion at 36.7 $R_\odot$	6 November
...	...
22nd perihelion at 9.86 $R_\odot$	24 December 2024

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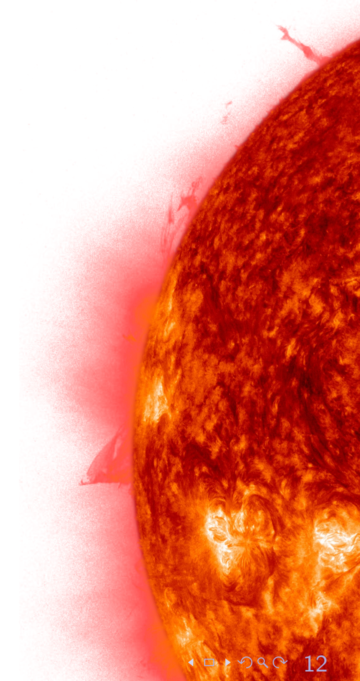

Empirical solar wind model

Aim of this study:

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

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

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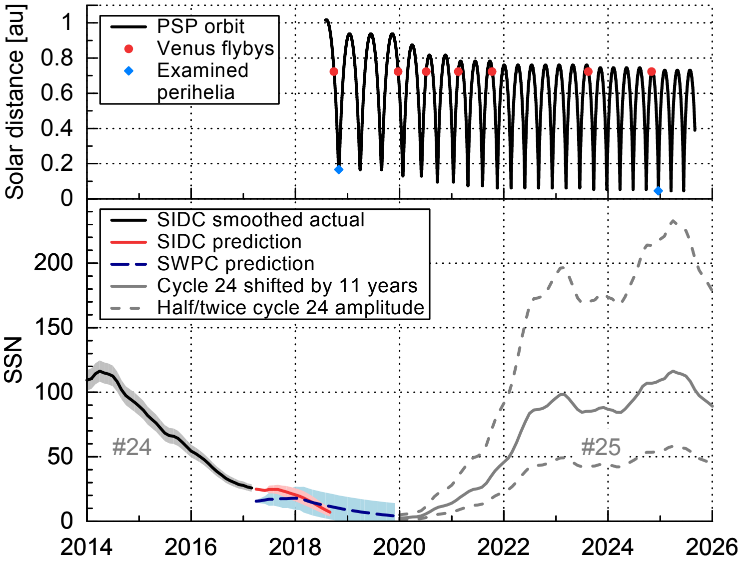
Concept of the model:
Frequency distributions shifted according to solar activity and solar distance

Solar wind key parameters

- Magnetic field strength
- Velocity
- Density
- Temperature

PSP distance and solar activity



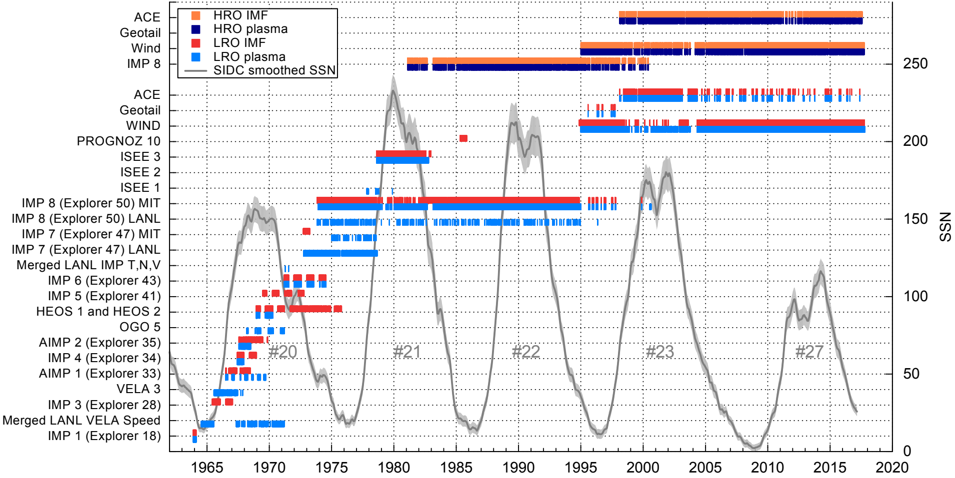
Credit: Venzmer & Bothmer (2018)

Perihelion #1
2018: solar minimum

Perihelion #22
2024: solar maximum

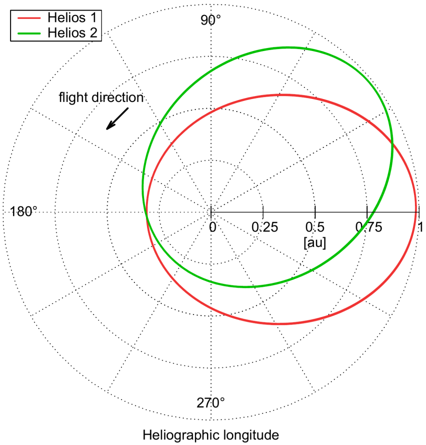
Solar wind data

OMNI data set (King & Papitashvili, 2005)
- intercalibrated multi-spacecraft data
- time-shifted to the bow shock of the magnetosphere
- hourly data since 1963



Solar wind data

Helios data set (Rosenbauer et al., 1977)
- Helios 1 and Helios 2 probes
- solar distance range 0.29–0.98 au
- hourly data from 1974–1981



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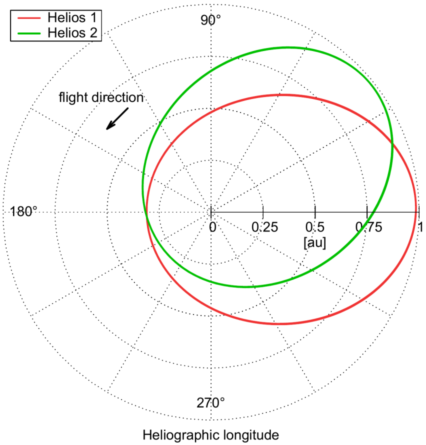

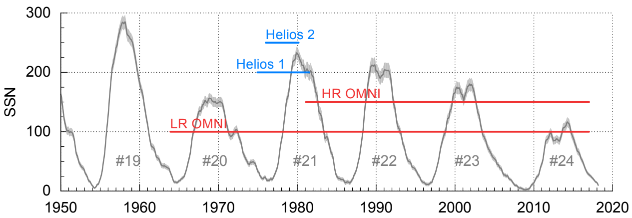

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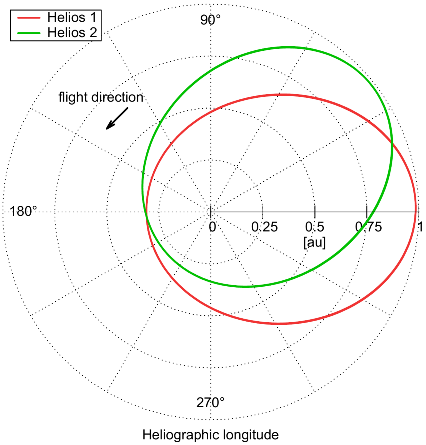
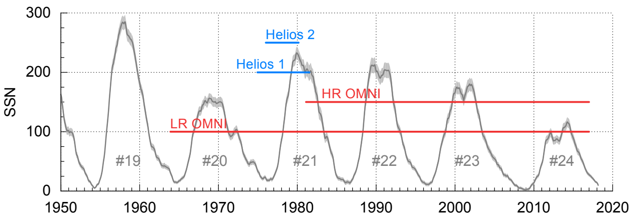
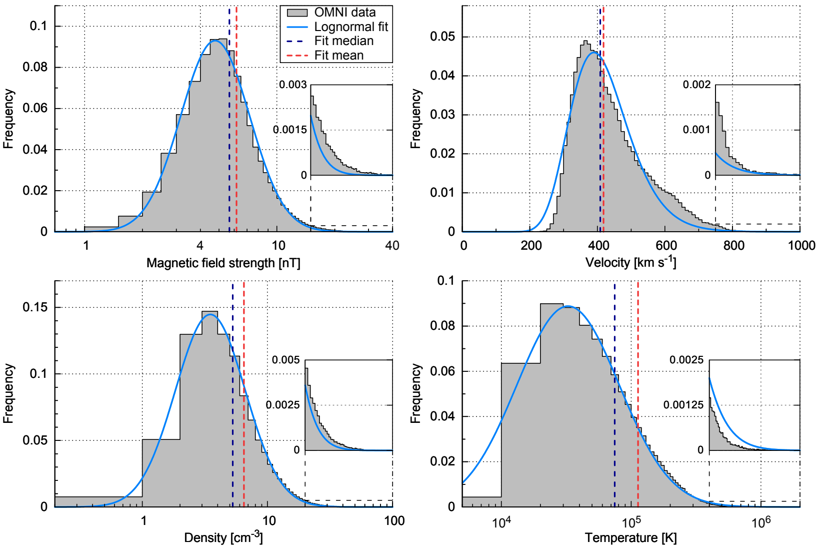




Solar wind model data use

- 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

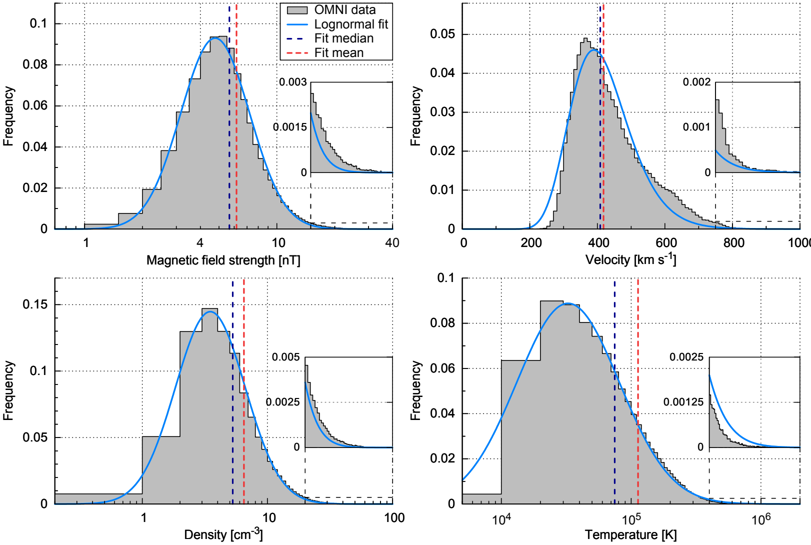
Hourly OMNI data from 1963 to 2016



Credit: Venzmer & Bothmer (2018)

Frequency distributions

Hourly OMNI data from 1963 to 2016



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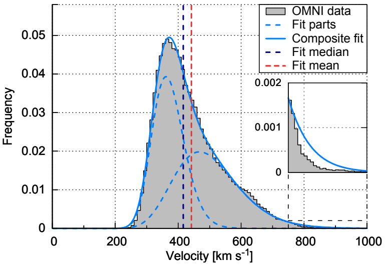

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Solar activity dependence

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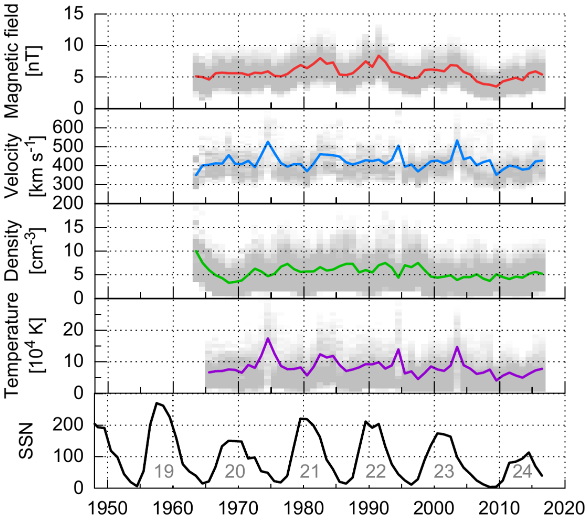

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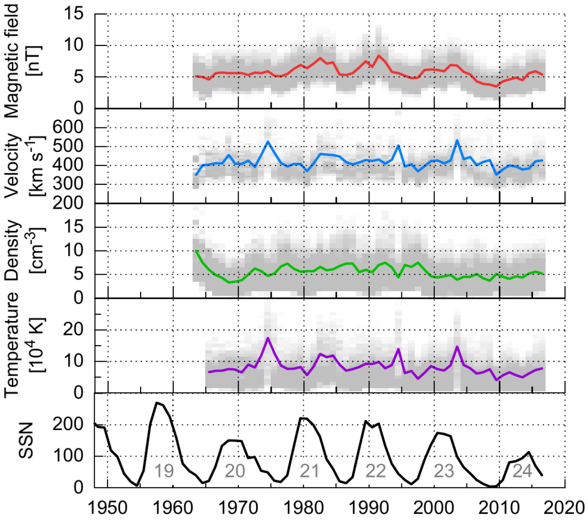

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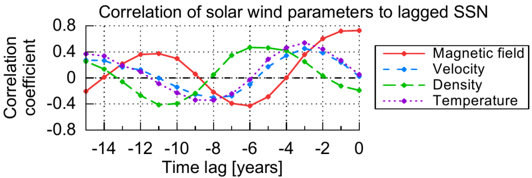

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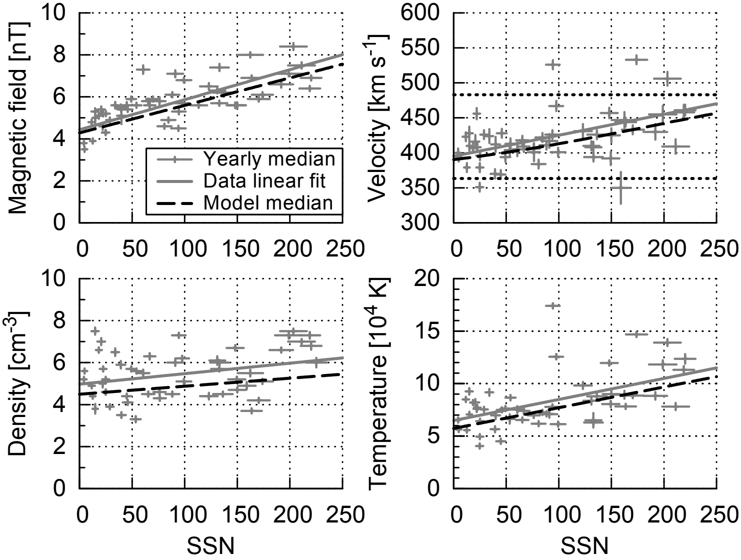

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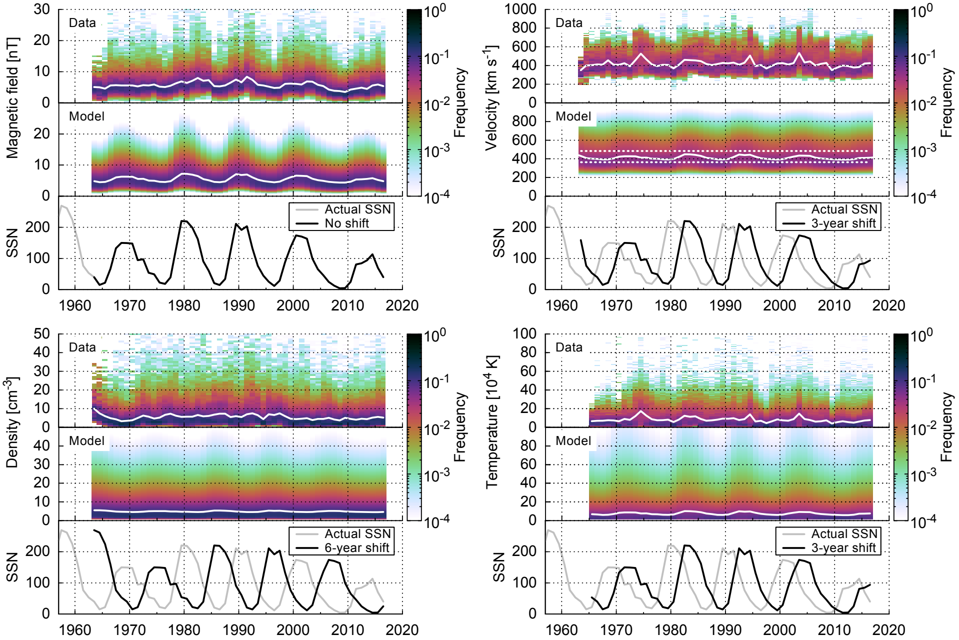
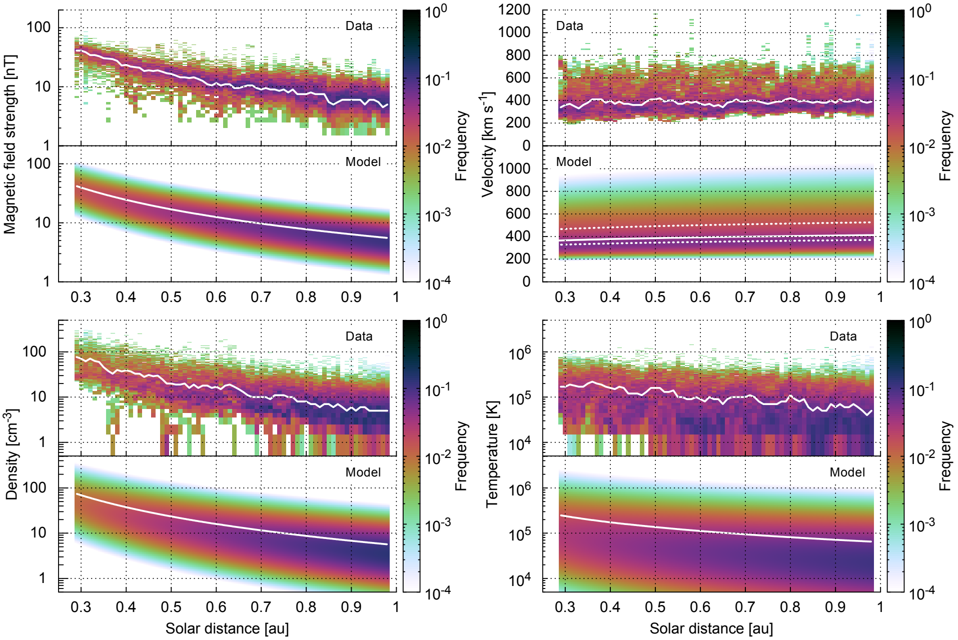


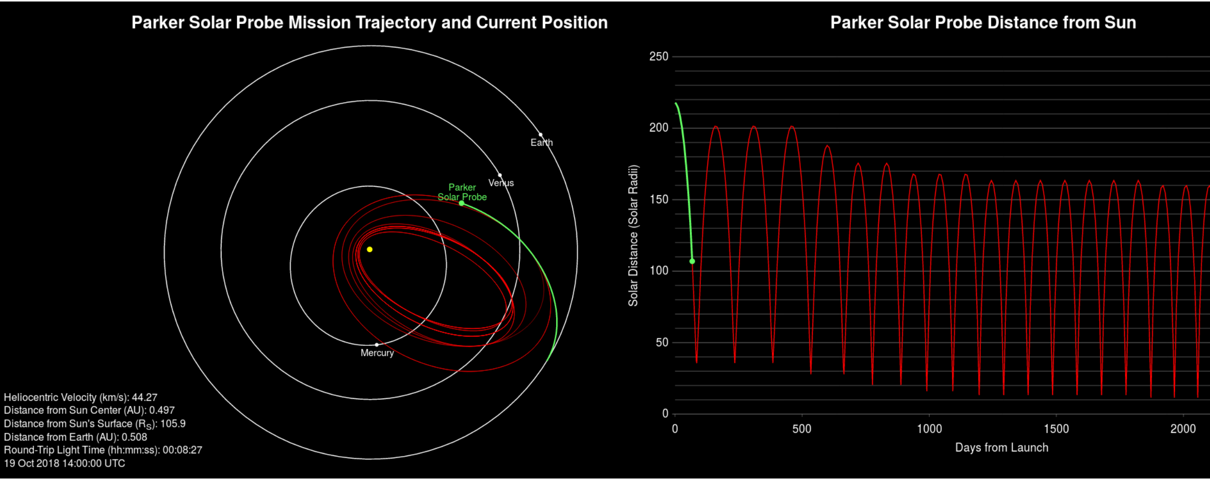
Credit: Venzmer & Bothmer (2018)

Solar distance dependence – Helios data



Credit: Venzmer & Bothmer (2018)

Prediction for PSP orbit



Credit: NASA

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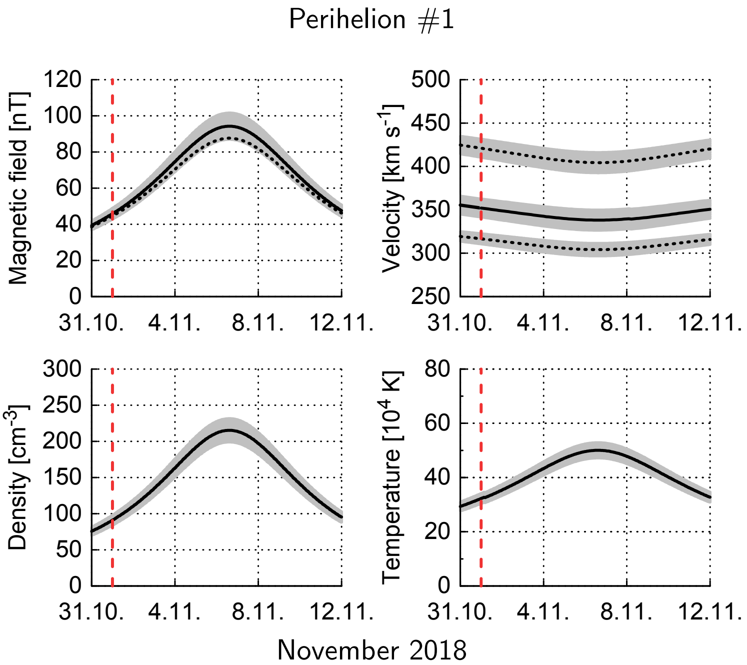

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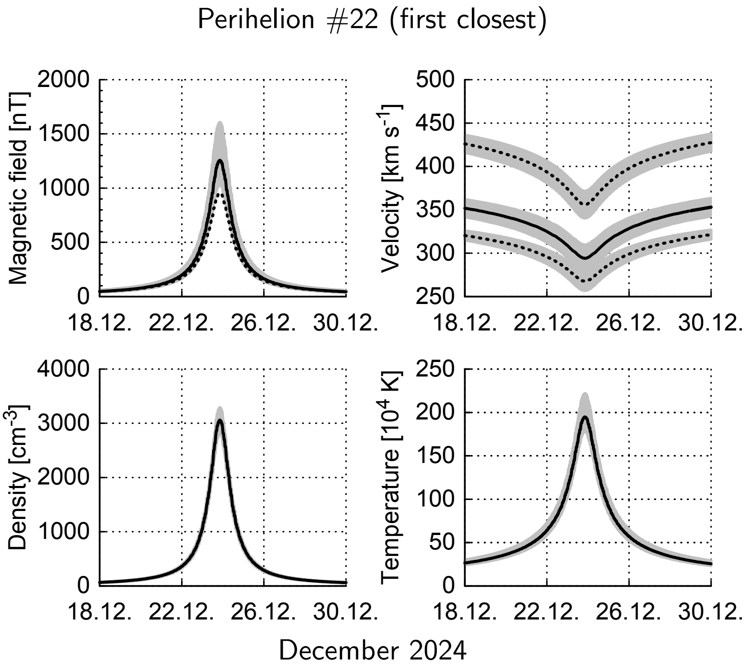

Comparison with other studies

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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Extrapolation results (Venzmer & Bothmer, 2018)

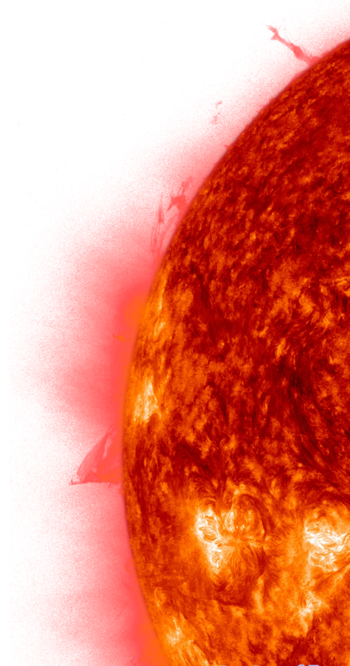
- Remote observations show the limits of the extrapolation
- Velocity and temperature are overestimated
- Solar wind is still being heated and accelerated in this region (up to 20 $R_\odot$)

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

Outlook

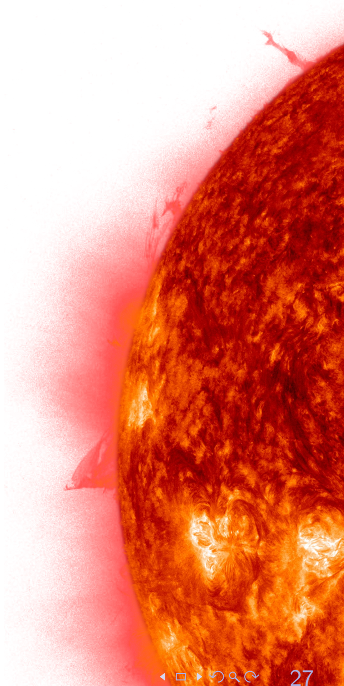
- Possible modifications to model (e.g., flux conservation)
- Refine model with additional solar wind data from Mercury probes and the upcoming Solar Orbiter mission
- Parker Solar Probe measurements can be used to validate the extrapolations



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
- Parker Solar Probe measurements can be used to validate the extrapolations

Thank you!



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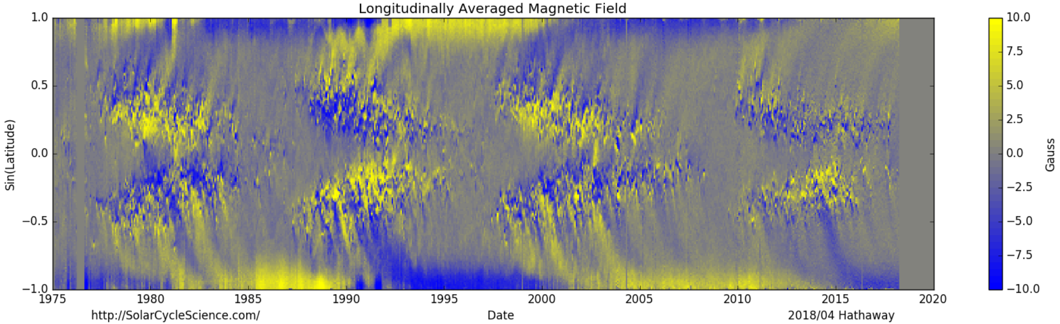
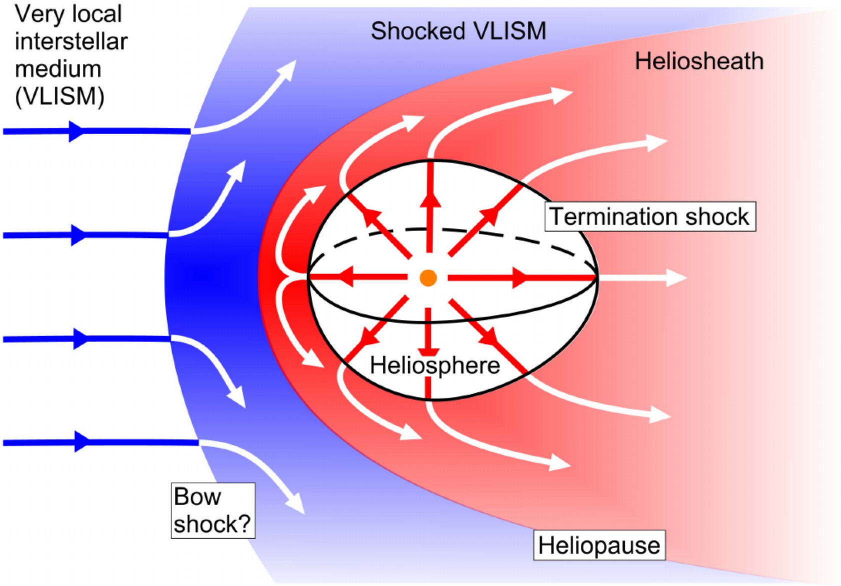
Solar activity

Magnetic butterfly diagram



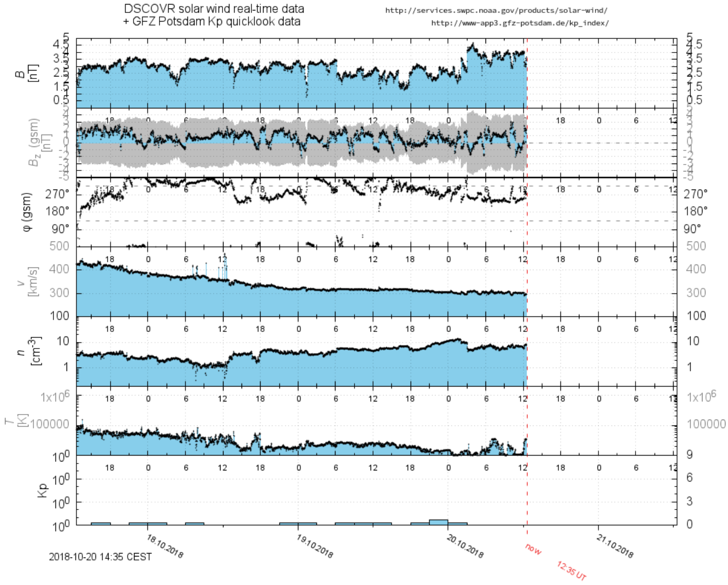
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

Solar wind



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

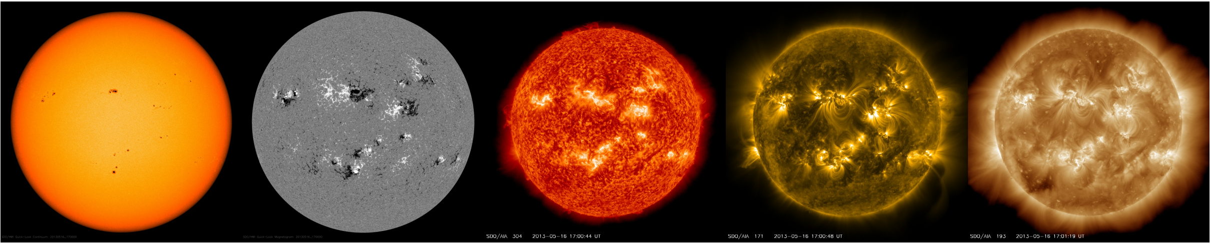
Solar wind



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]
B_z (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

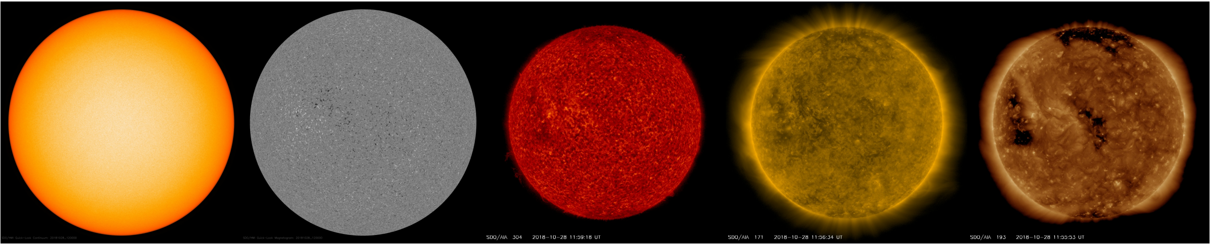
Solar surface and atmosphere

Intensitygram	Magnetogram	304 Å	171 Å	193 Å



Credit: NASA SDO/HMI, 16 May 2013

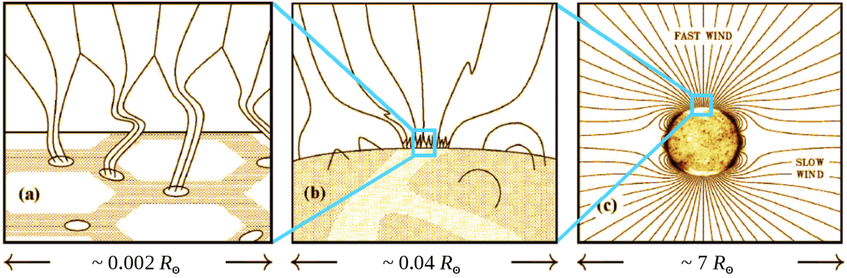
Credit: NASA SDO/AIA, 16 May 2013



Credit: NASA SDO/HMI, 28 Oct ober 2018

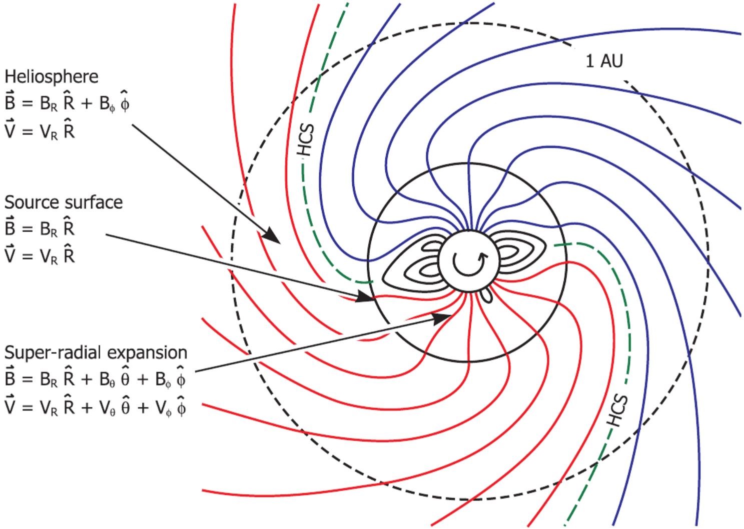
Credit: NASA SDO/AIA, 28 October 2018

Solar magnetic field



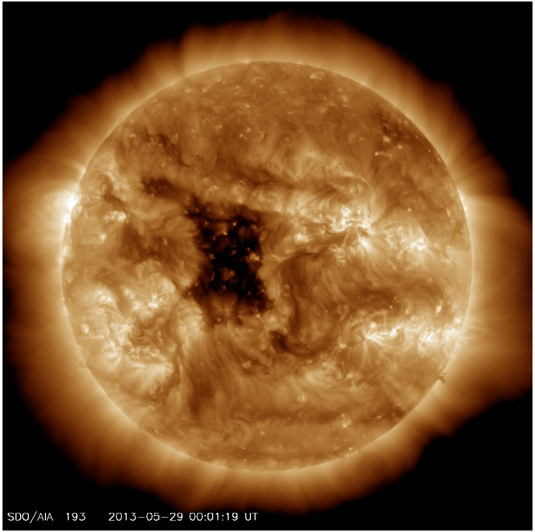
Courtesy of S. R. Cranmer

Solar magnetic field



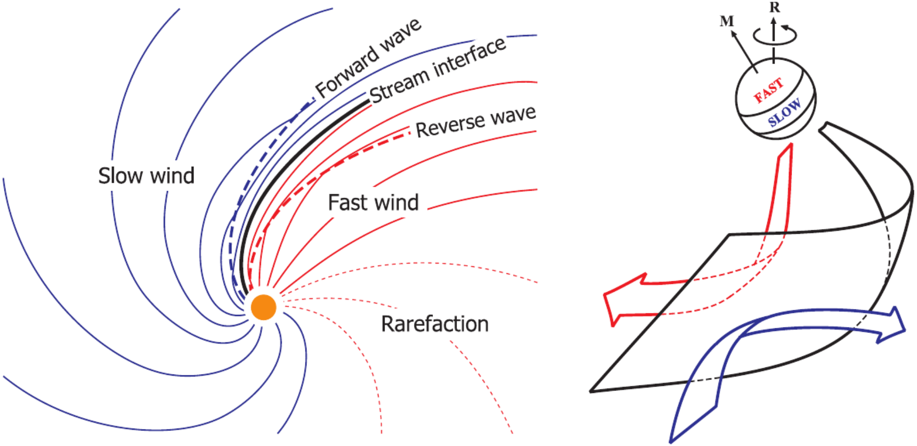
Credit: Owens & Forsyth (2013, Fig. 1), adapted from Schatten et al. (1969, Fig. 1)

Slow and fast solar wind



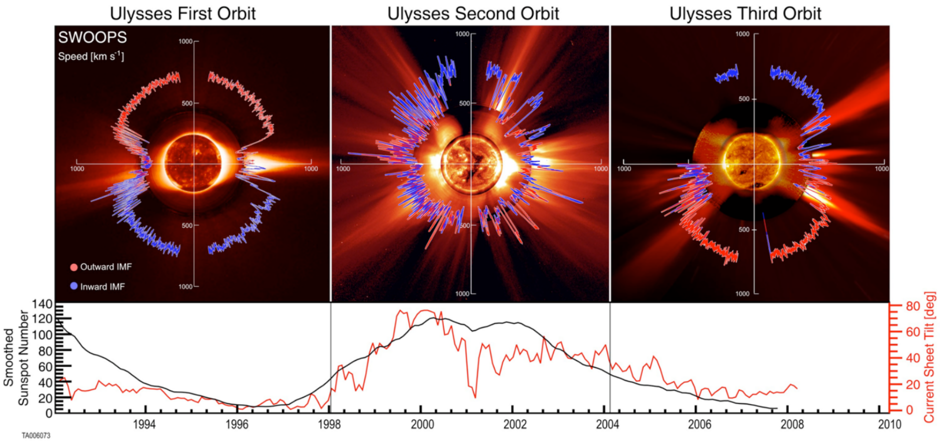
Credit: NASA/SDO and the AIA, EVE and HMI science teams

Slow and fast solar wind



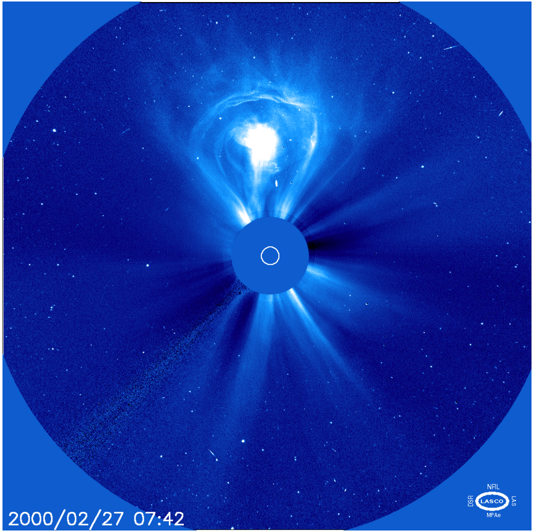
Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

Solar activity



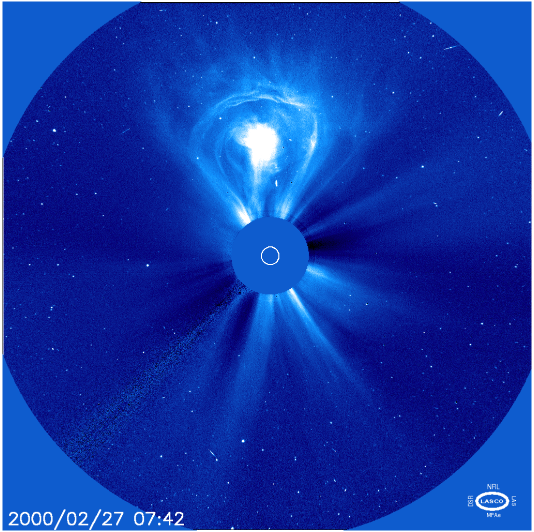
Credit: McComas et al. (2008a, Fig. 1)

Coronal mass ejections

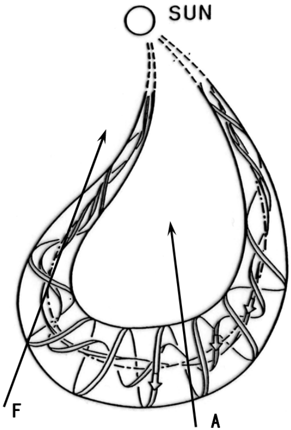


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

Coronal mass ejections

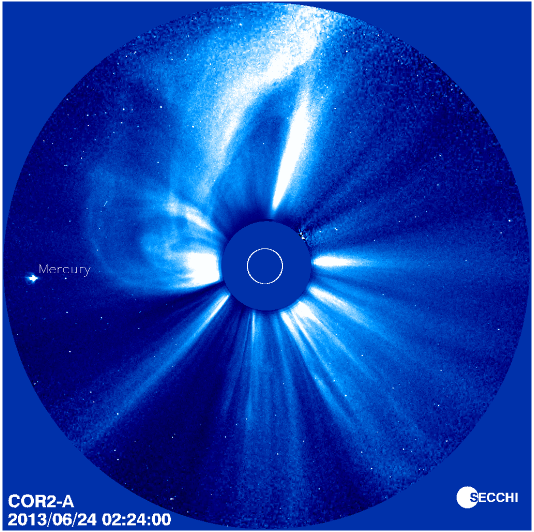


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

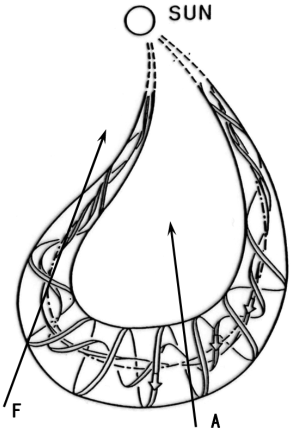


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections

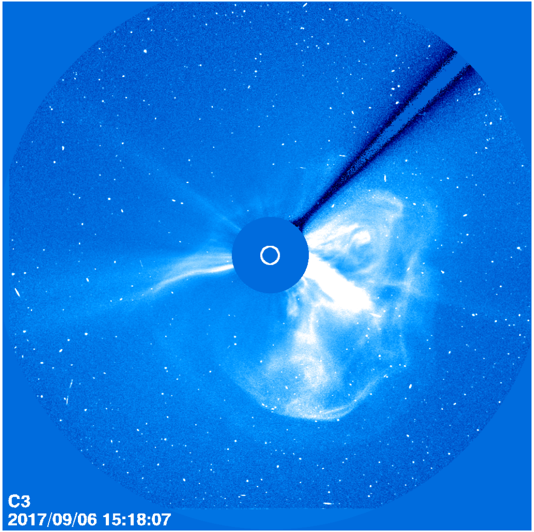


Courtesy of STEREO/COR2 consortium (NASA)

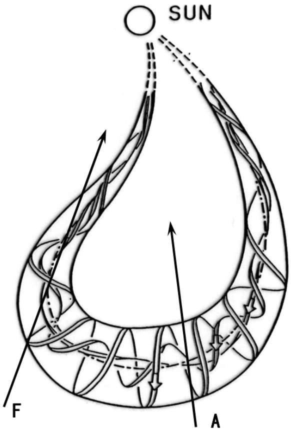


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections

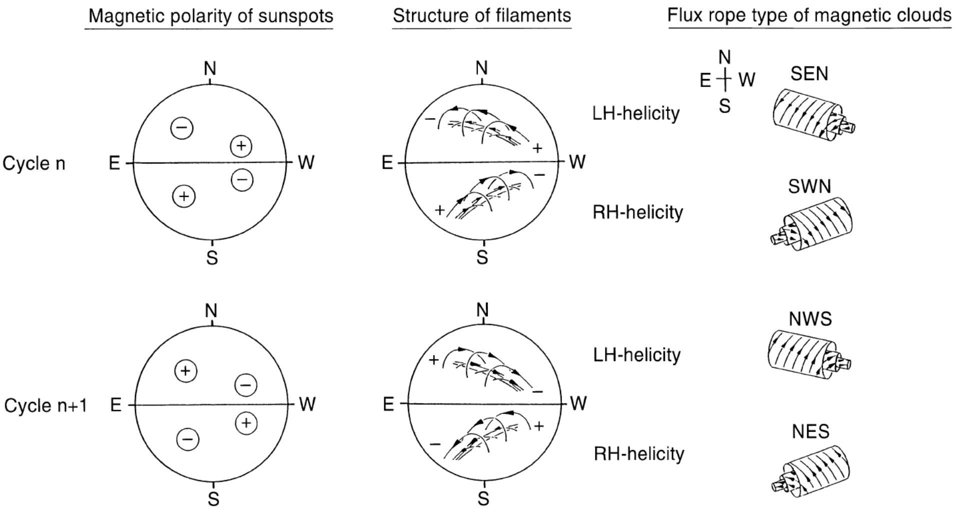


Courtesy of SOHO/LASCO consortium; SOHO is a project of international cooperation between ESA and NASA

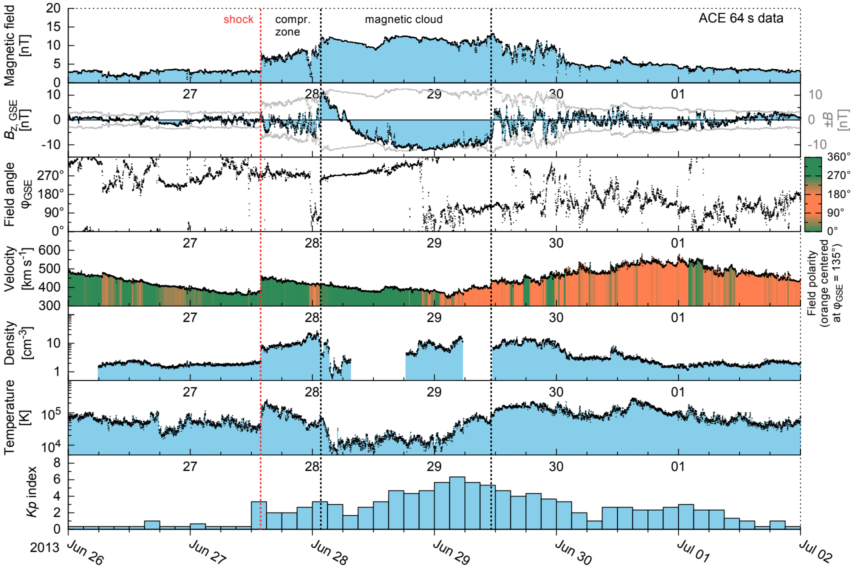


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

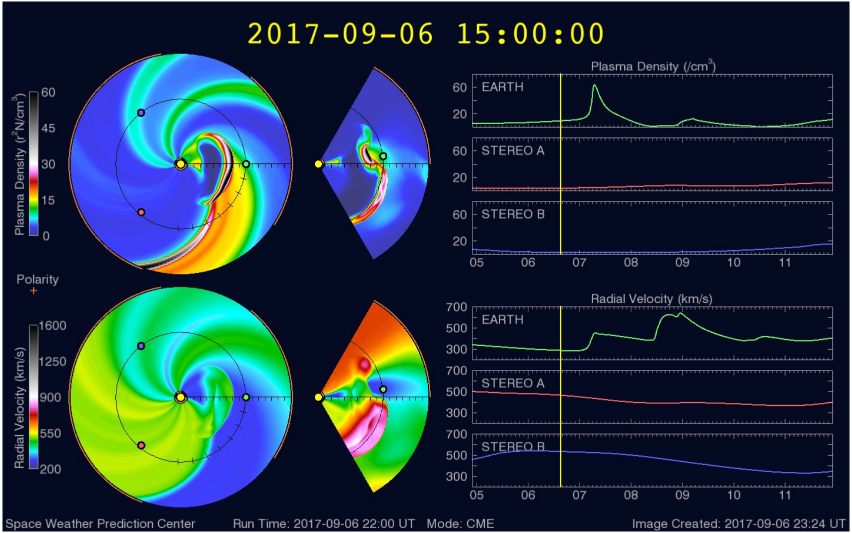
CME orientation



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

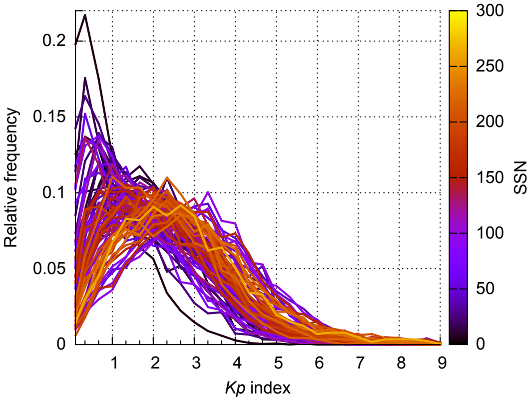

shock
compr. zone
magnetic cloud
ACE 64 s data
Magnetic field [nT]
Bz, GSE [nT]
±B [nT]
Field angle φGSE
Field polarity (orange centered at φGSE = 135°)
Velocity [km s-1]
Density [cm-3]
Temperature [K]
Kp index
2013
Jun 26
Jun 27
Jun 28
Jun 29
Jun 30
Jul 01
Jul 02

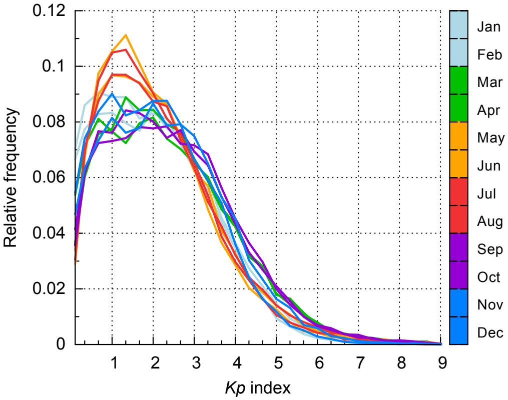
Solar wind and CME forecast



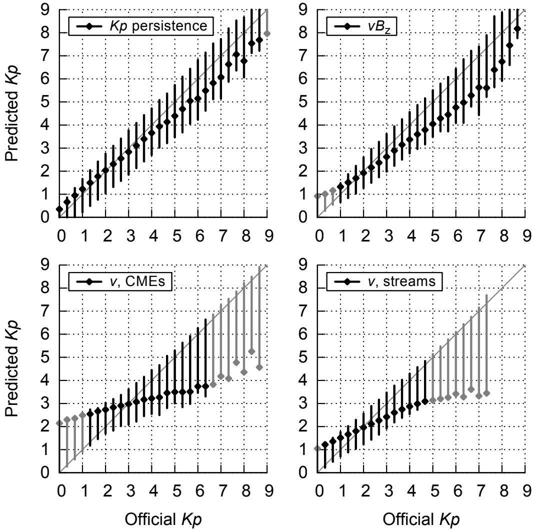
Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

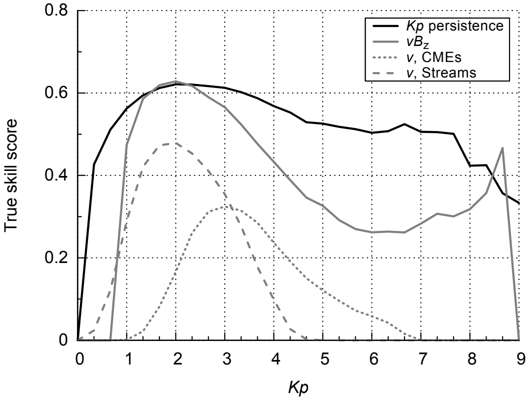
Kp long-term variations



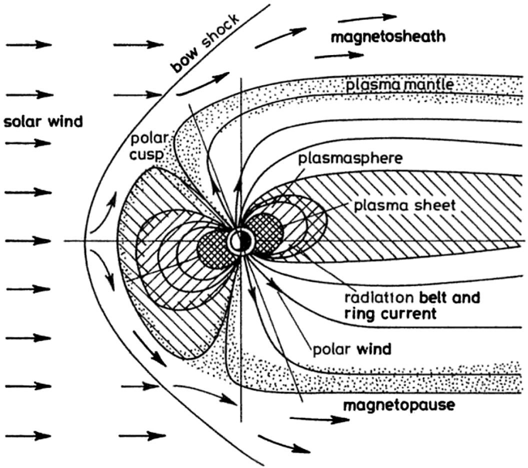


Prediction performance





Magnetosphere

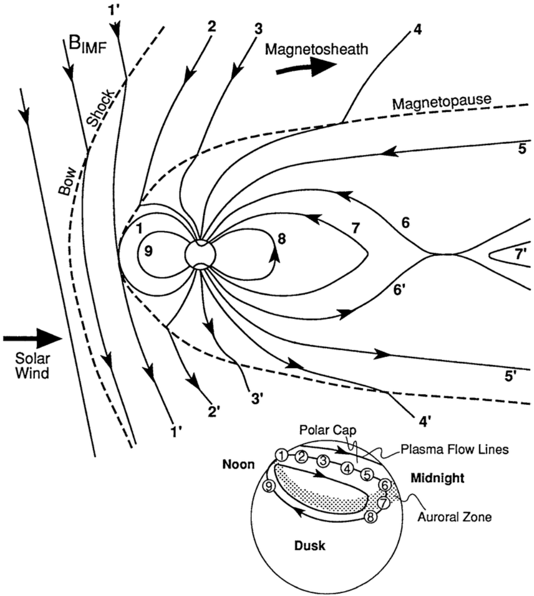


Credit: Davies (1990, Fig. 2.12)

Interaction mechanisms between solar wind and magnetosphere:

- Reconnection
- Turbulence
- Compression
- Induction

Magnetosphere



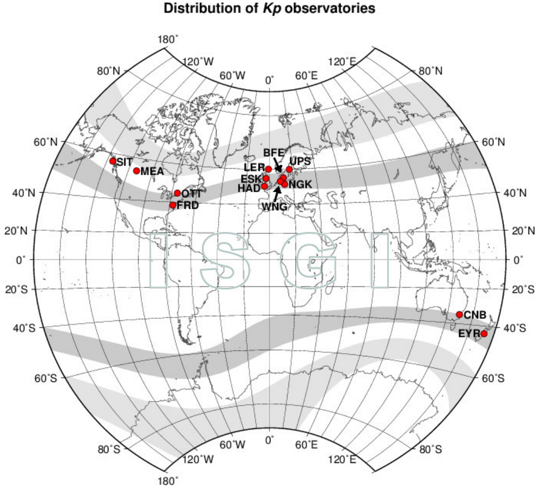
Credit: Hughes (1995, Fig. 9.11)

Factors that influence the reconnection flux rate:

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

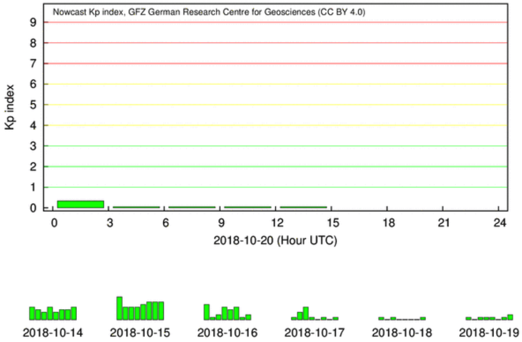
Kp index

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



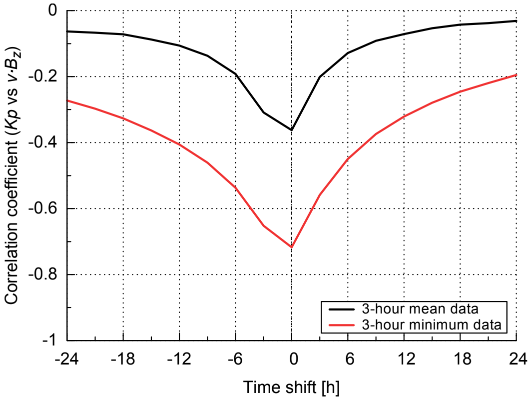
Courtesy of International Service of Geomagnetic Indices (ISGI), 2013

Kp index
Quicklook *Kp*

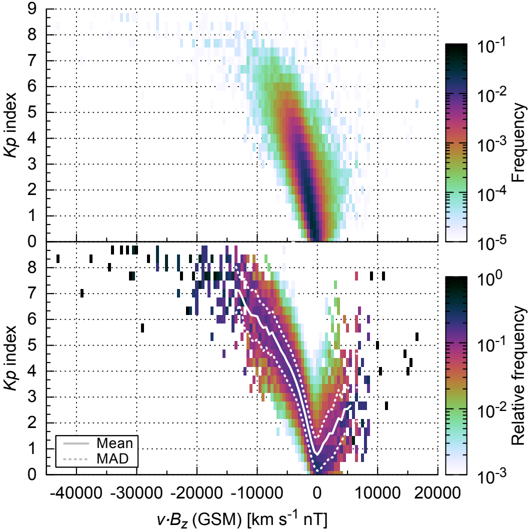


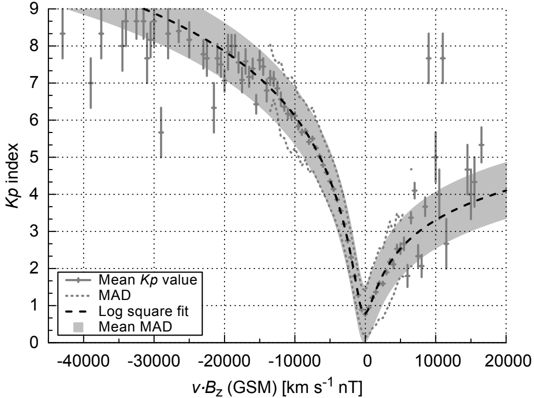
Credit: GFZ Potsdam, 2018

Solar wind electric field

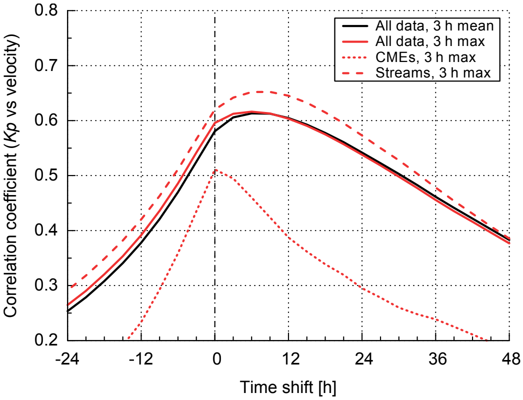


Solar wind electric field

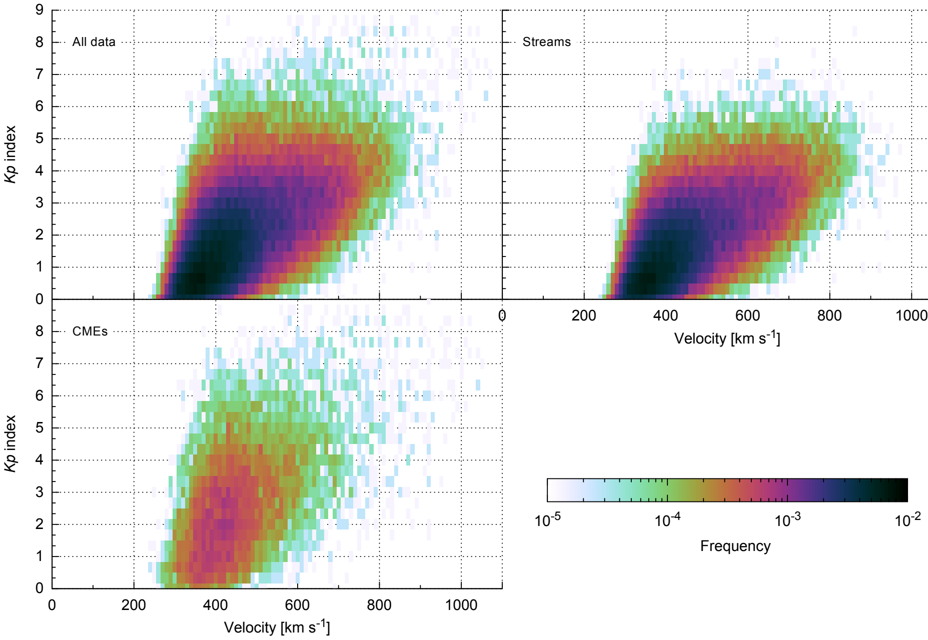


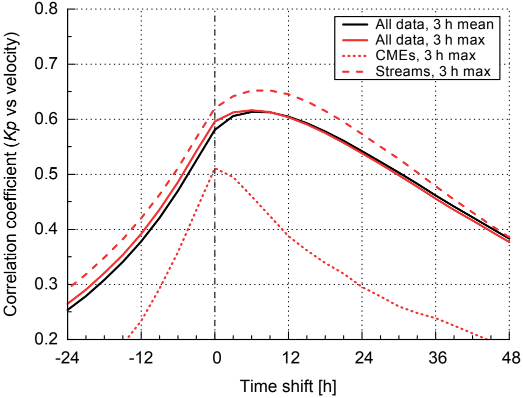


Solar wind velocity



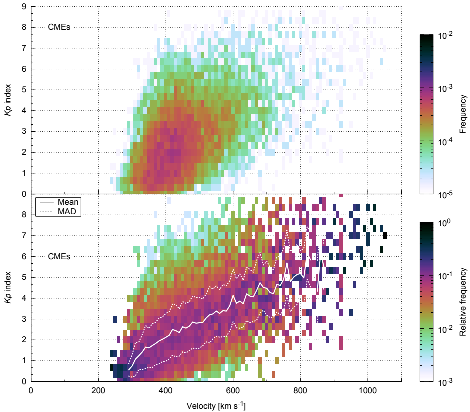
Solar wind velocity

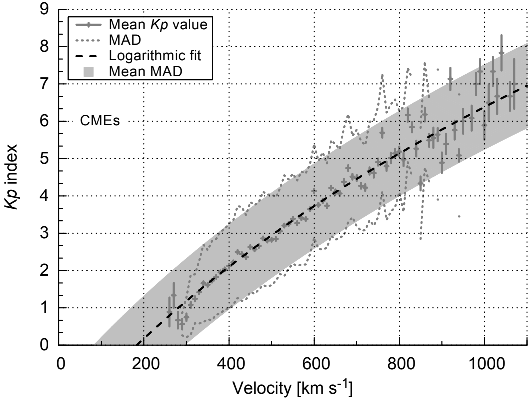




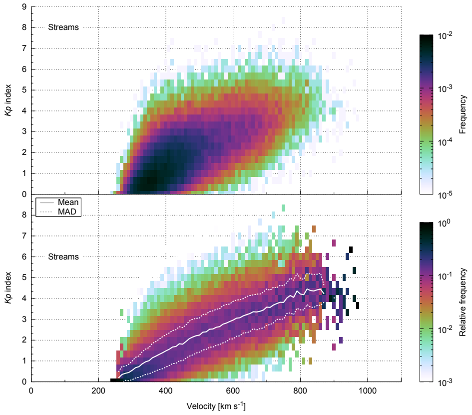
All data, 3 h mean
All data, 3 h max
CMEs, 3 h max
Streams, 3 h max
Correlation coefficient (Kp vs velocity)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-24
-12
0
12
24
36
48
Time shift [h]

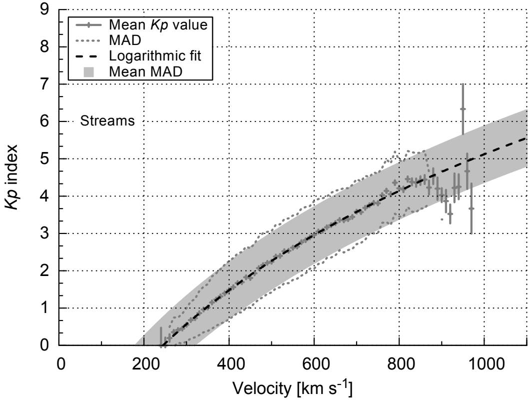
CME velocity

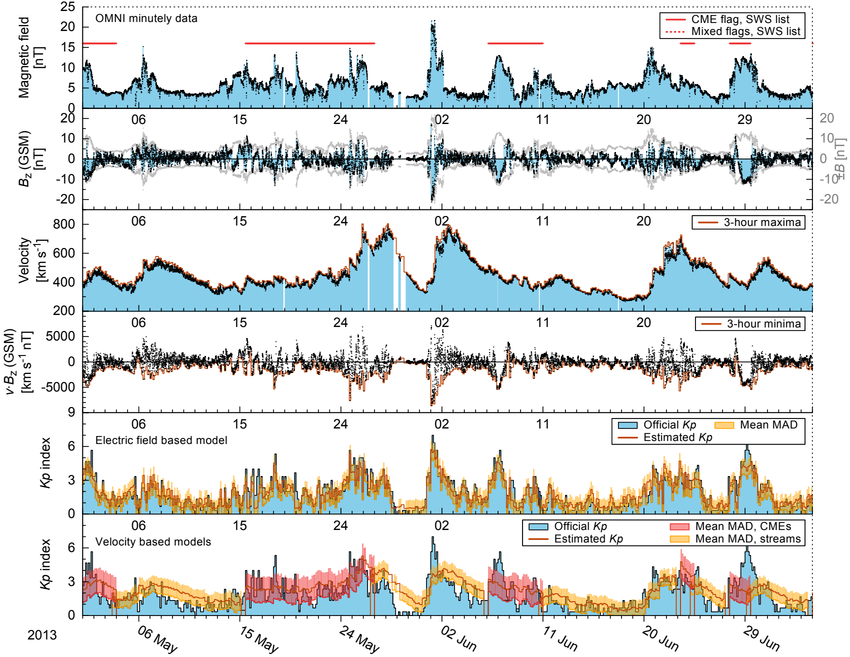




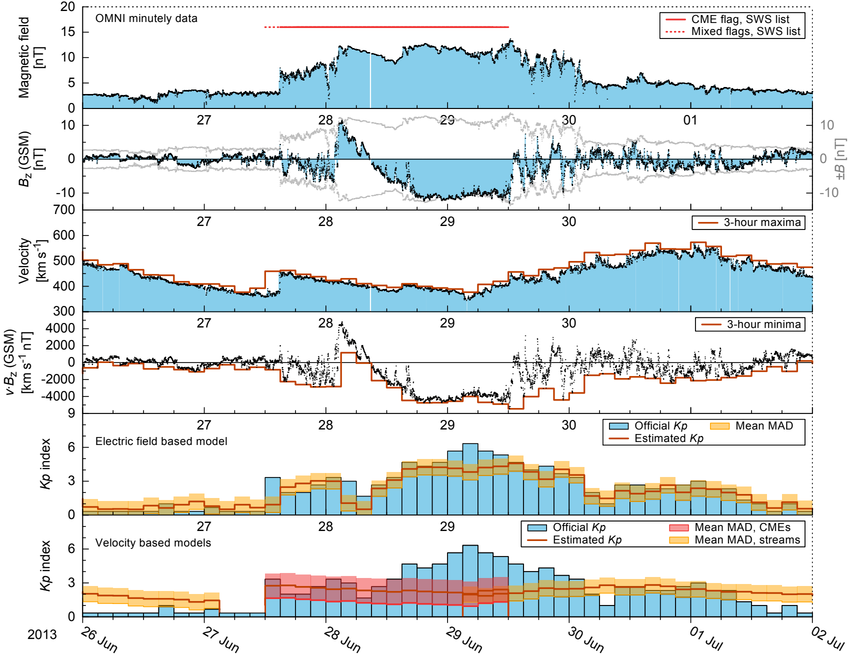
Stream velocity







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]
$\pm B$ [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
Estimated Kp
Mean MAD
Kp index
Velocity based models
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

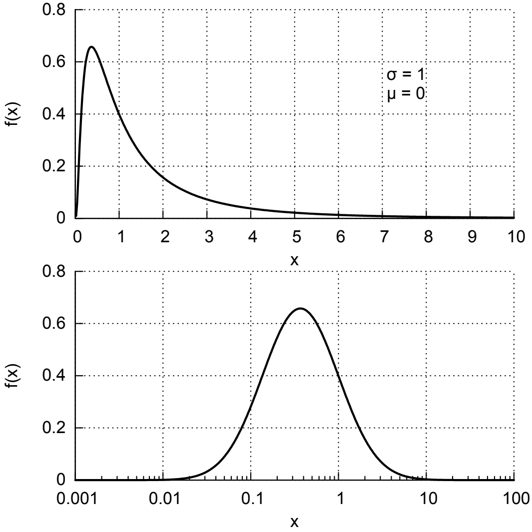
- Solar wind electric field proxy (vB_z)
- Velocity of CME-associated flows (v_{CME})
- Velocity of solar wind streams (v_{stream})

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

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).

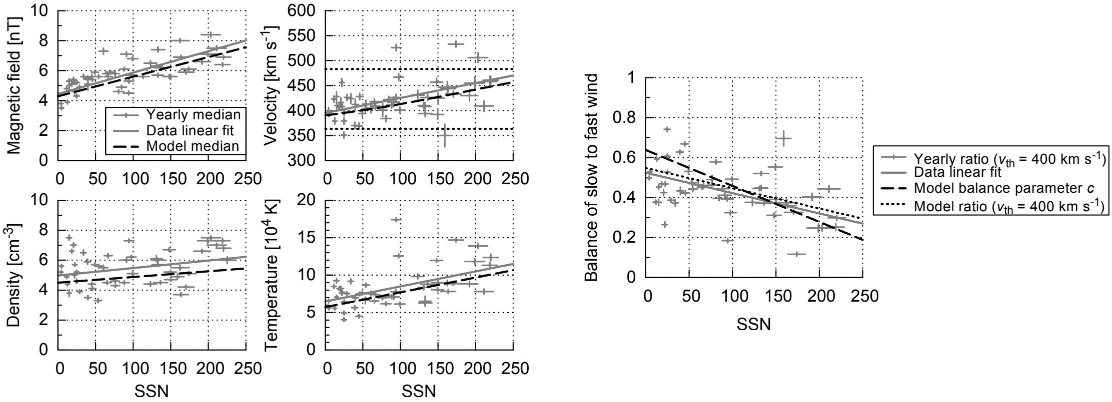
Median and average:

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

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

Near-Sun region

Unsolved problems: - Coronal heating mechanisms
- Solar wind acceleration processes
- Solar energetic particle sources


Magnetic field [nT]
Yearly median
Data linear fit
Model median
Velocity [km s-1]
Density [cm-3]
Temperature [10^4 K]
SSN
SSN
Balance of slow to fast wind
SSN
Yearly ratio (vth = 400 km s-1)
Data linear fit
Model balance parameter c
Model ratio (vth = 400 km s-1)

PSP perihelia prediction