

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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Georg-August-Universität Göttingen

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Thursday, 1 November 2018, 14:00

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

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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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Empirical solar wind model

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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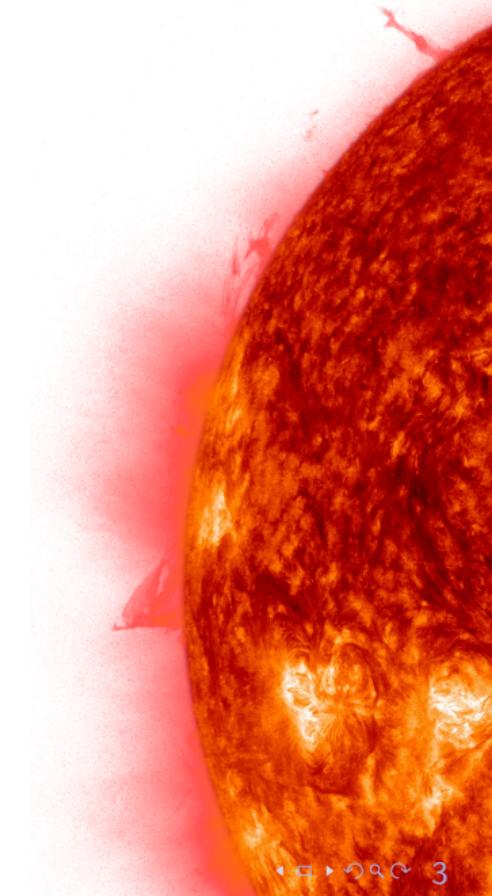
- Solar wind electric field
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Empirical solar wind model

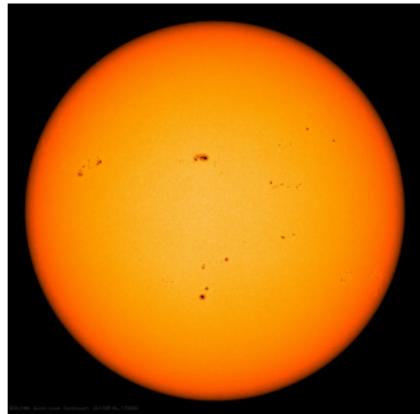
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- Introduction
 - Solar activity
 - Solar wind
 - Parker Solar Probe (PSP)
 - Empirical solar wind model
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 - Prediction for PSP orbit
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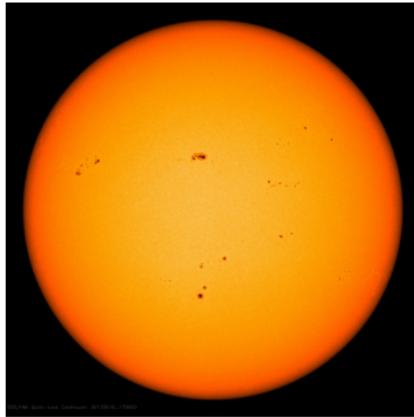


Solar activity

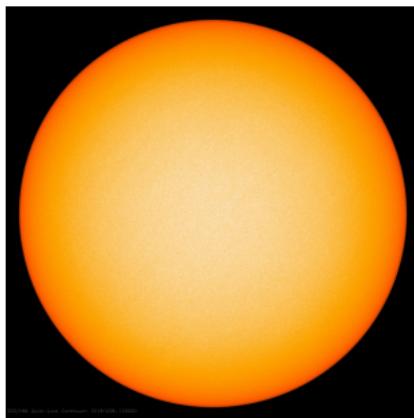


Credit: NASA SDO/HMI, 16 May 2013

Solar activity

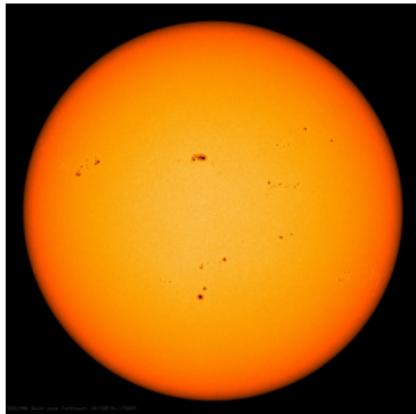


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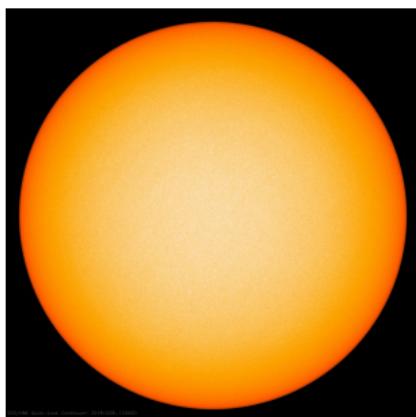


Credit: NASA SDO/HMI, 28 October 2018

Solar activity

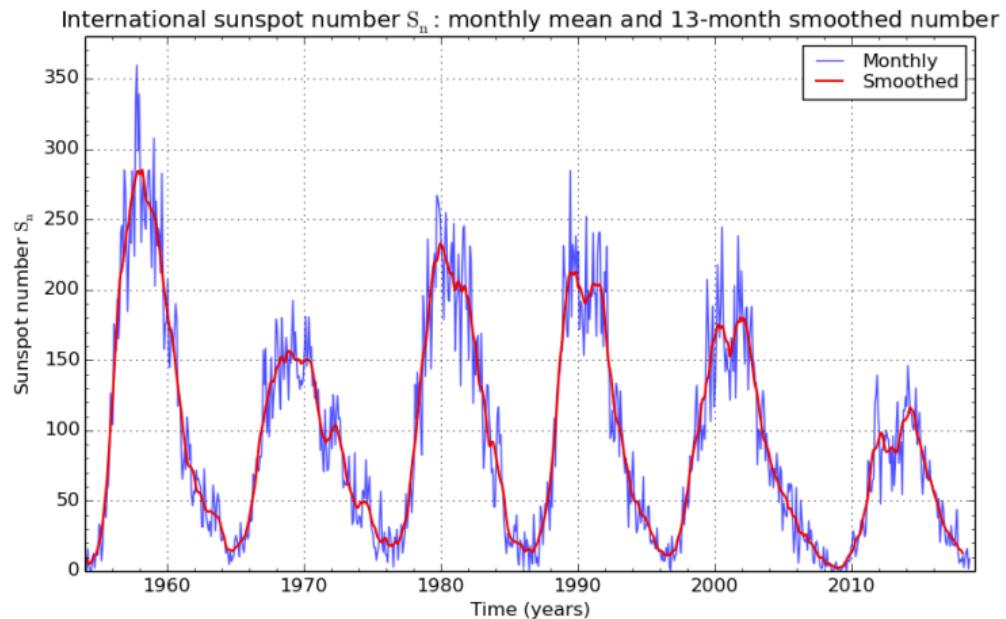


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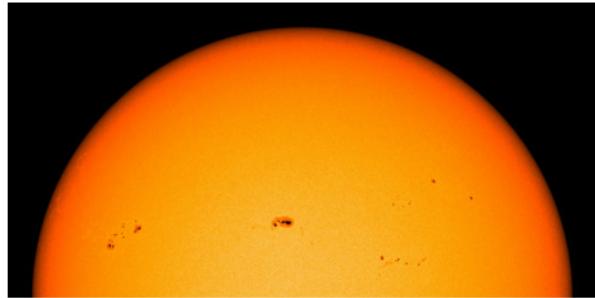
Credit: NASA SDO/HMI, 28 October 2018

11-year sunspot number cycle

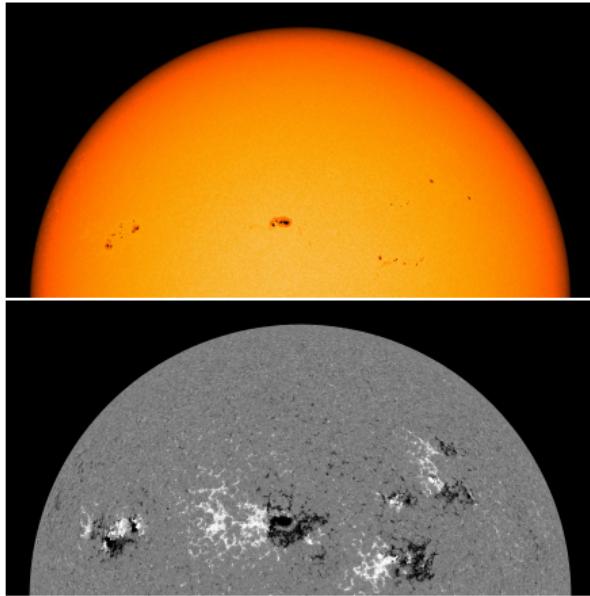


SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2018 September 1

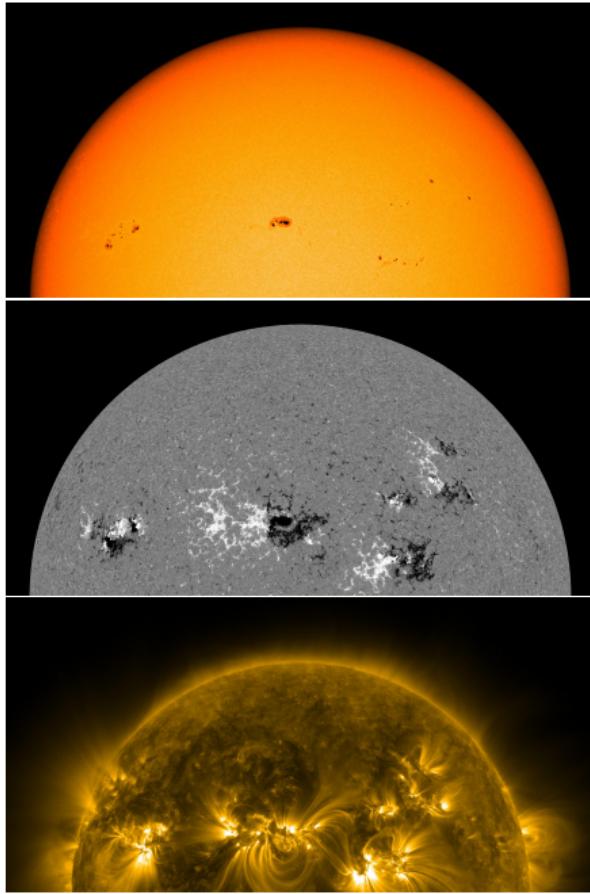
Solar activity



Solar activity

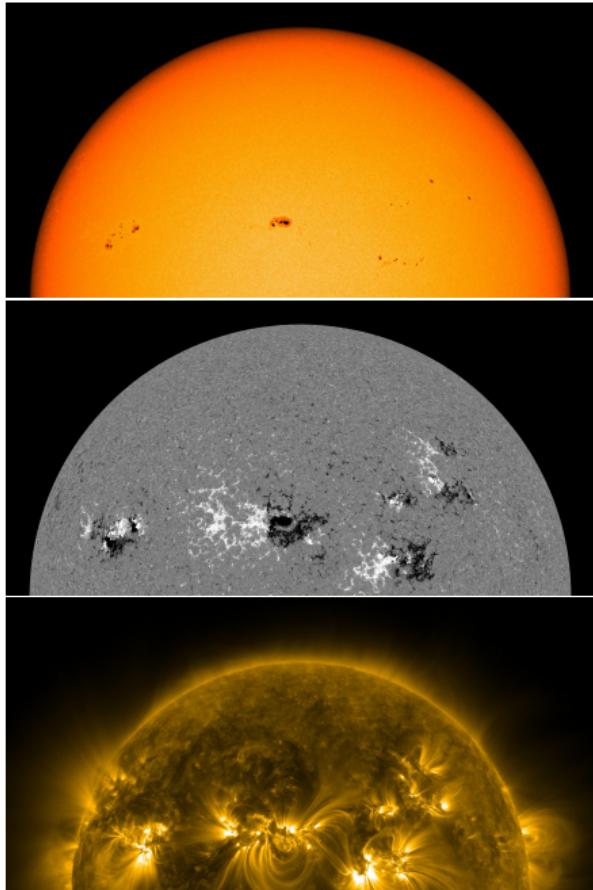


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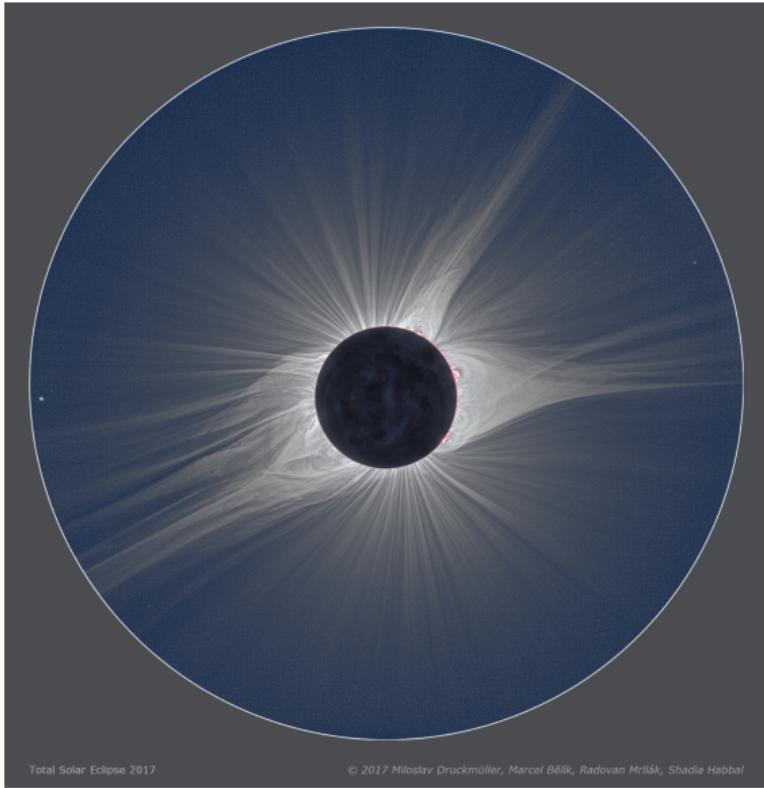


Credit: NASA SDO/HMI and SDO/AIA, 16 May 2013

Solar activity



Credit: NASA SDO/HMI and SDO/AIA, 16 May 2013



Total Solar Eclipse 2017

© 2017 Miloslav Druckmüller, Marcel Bělák, Radovan Mrálek, Shadia Habbal

Credit: Miloslav Druckmüller, Marcel Bělák, Radovan Mrálek, Shadia Habbal, 2017

Solar wind

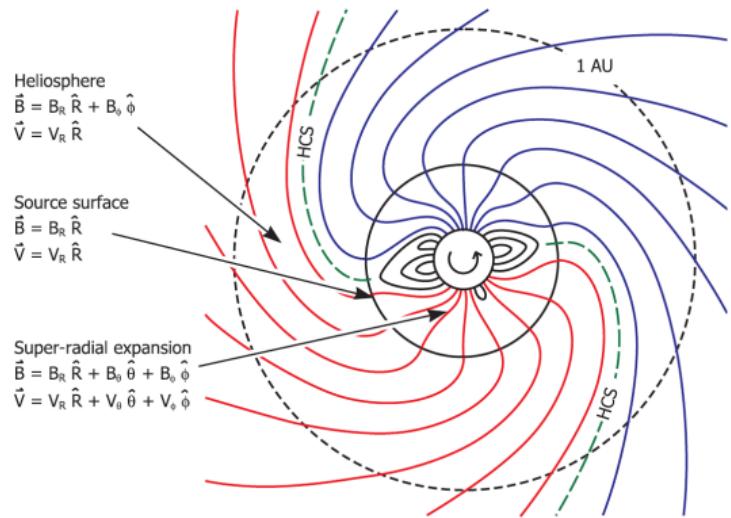
Solar wind

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

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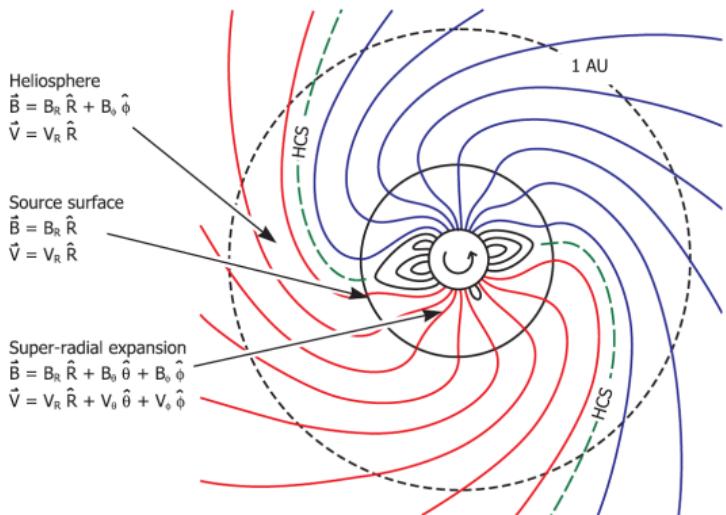


Credit: Owens & Forsyth (2013, Fig. 1), adapted from Schatten et al. (1969, Fig. 1)

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

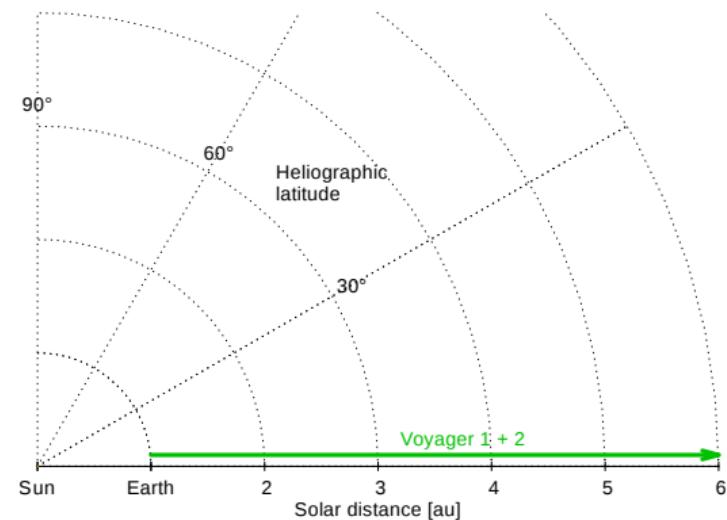


Credit: Owens & Forsyth (2013, Fig. 1), adapted from Schatten et al. (1969, Fig. 1)

Solar wind

Measured in-situ throughout the heliosphere:

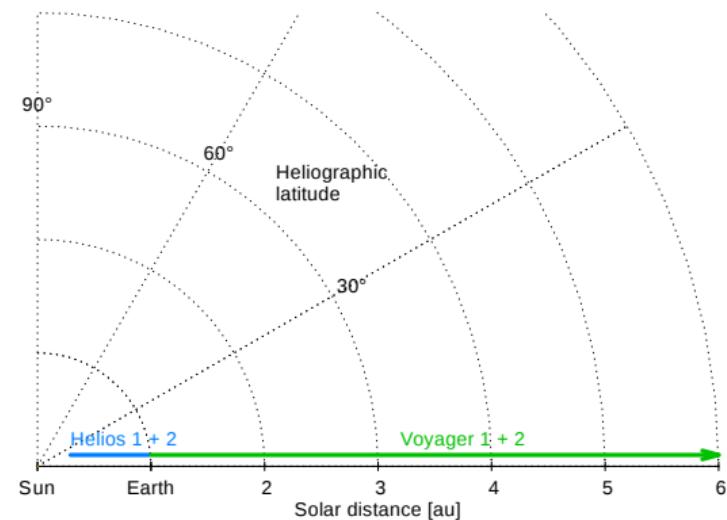
- Voyager 1 & 2 – out to heliopause (1–120 au)



Solar wind

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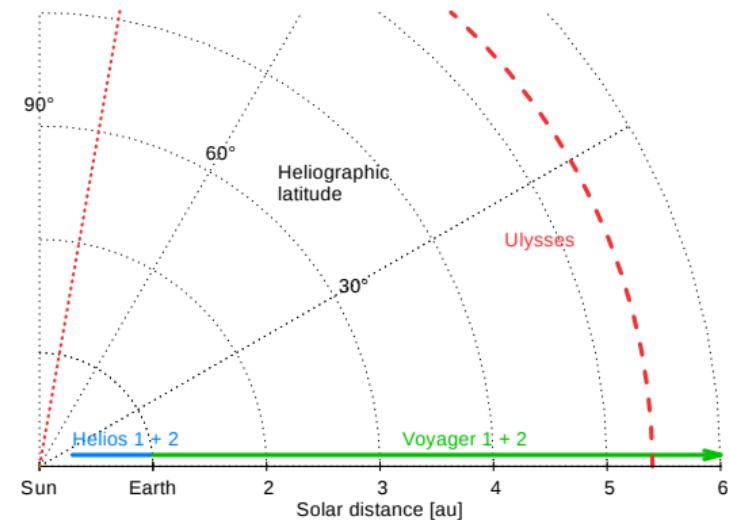
- Voyager 1 & 2 – out to heliopause (1–120 au)
- Helios 1 & 2 – down to Mercury (0.29–0.98 au)



Solar wind

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



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 problem
- Solar wind acceleration

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 and transport solar energetic particles

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

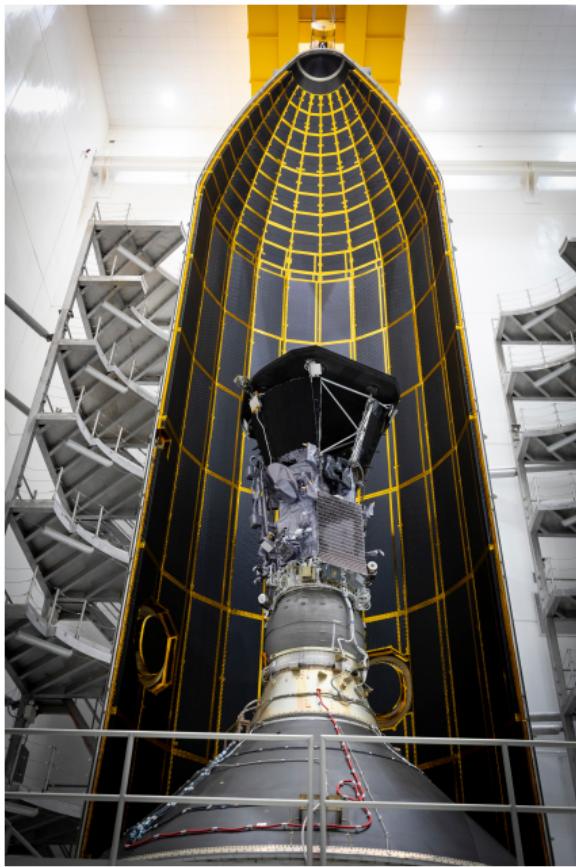
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Scientific instruments

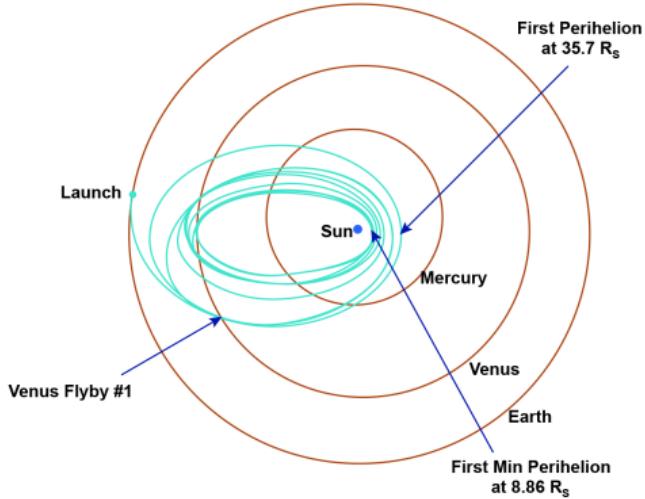
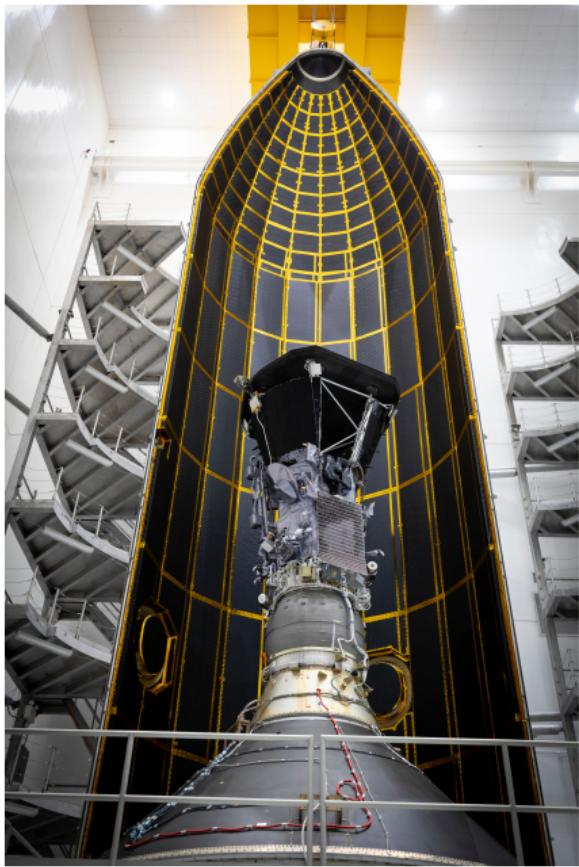
- FIELDS – Electromagnetic Fields Investigation
- IS \odot IS – Integrated Science Investigation of the Sun
- SWEAP – Solar Wind Electrons Alphas and Protons Investigation
- WISPR – Wide-Field Imager for Solar Probe

Parker Solar Probe



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

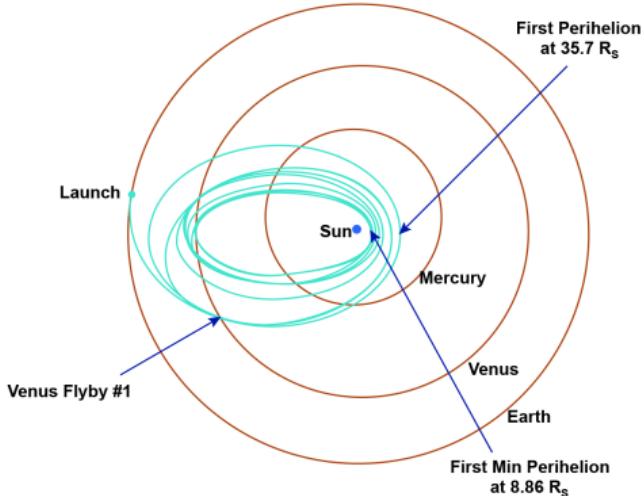
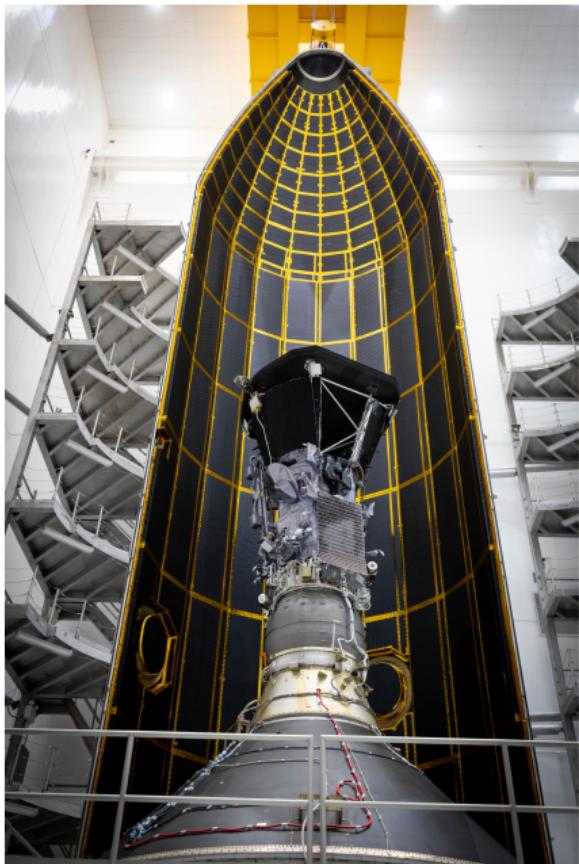
Parker Solar Probe



Credit: NASA/Johns Hopkins APL, 2018

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

Parker Solar Probe



Credit: NASA/Johns Hopkins APL, 2018

Launch

1st Venus flyby

Sun-closest spacecraft ever

1st perihelion at $36.7 R_\odot$

...

22nd perihelion at $9.86 R_\odot$

12 August 2018

3 October

29 October

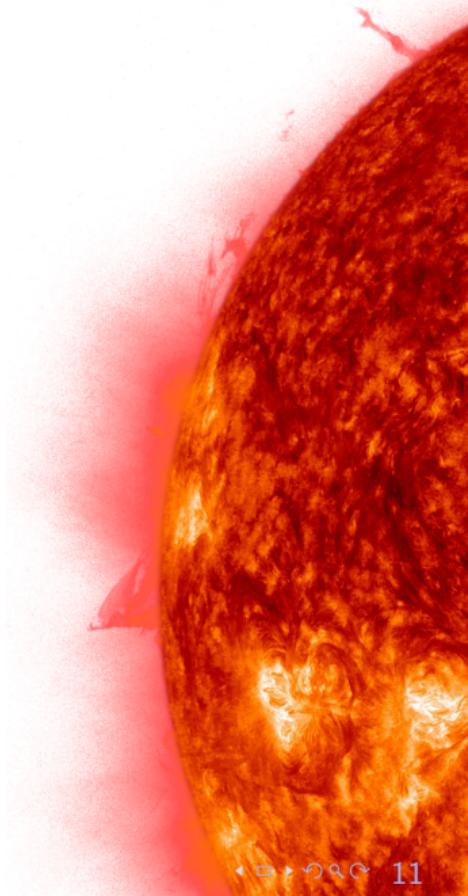
6 November

...

24 December 2024

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

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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
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The article is based on my work performed for the
CGAUSS (Coronagraphic German and US
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Solar wind environment (key parameters)

- Magnetic field strength
- Velocity
- Density
- Temperature

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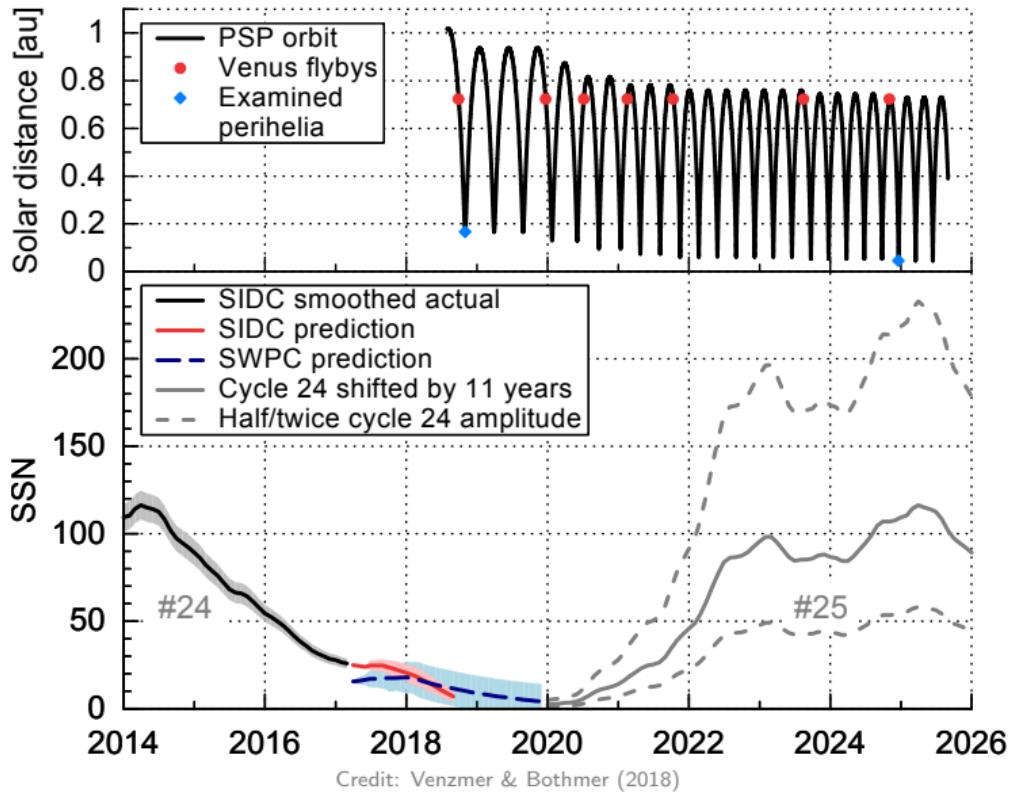
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Uniqueness of the model:

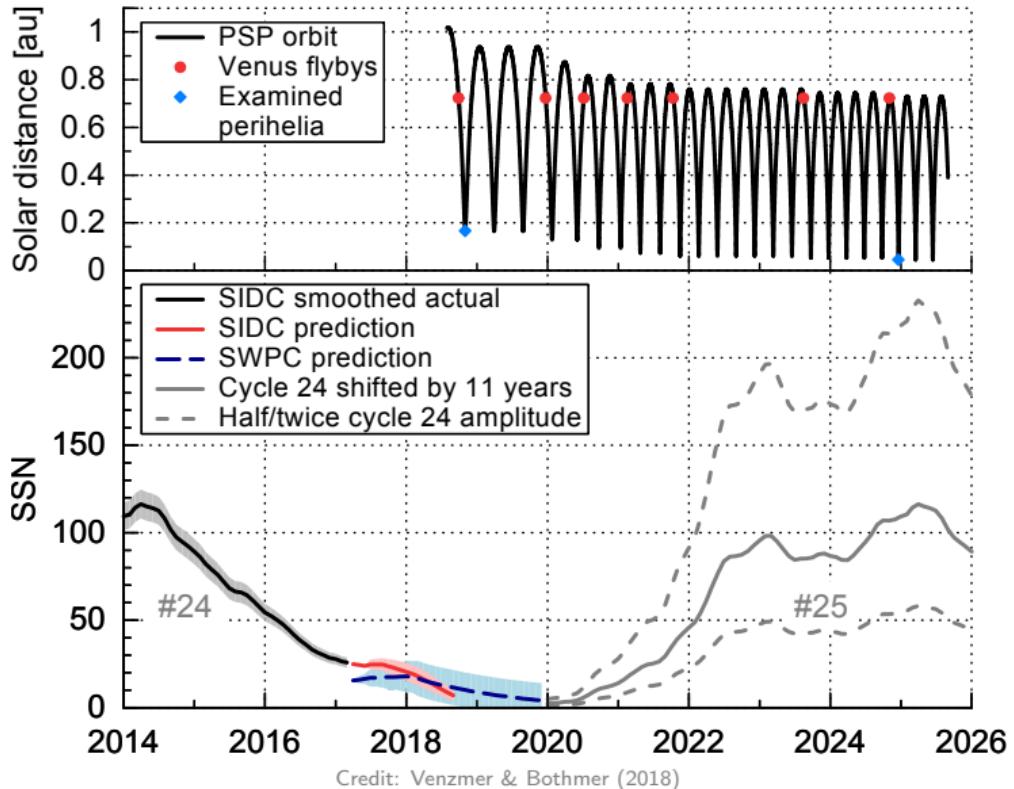
- Solar wind parameters are represented by frequency distributions instead of average values

PSP distance and solar activity



Credit: Venzmer & Bothmer (2018)

PSP distance and solar activity



Perihelion #1
2018: solar minimum

Perihelion #22
2024: solar maximum

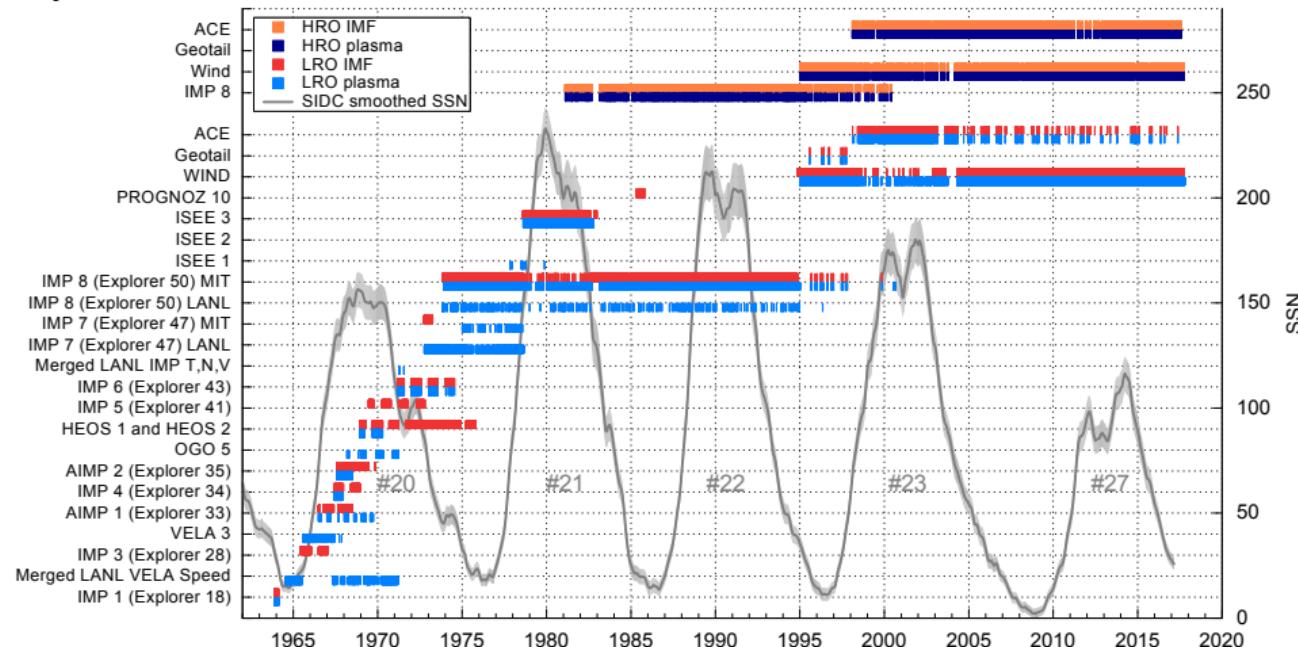
⇒ Predictions have to be dependent on

- solar distance
- solar activity (SSN)

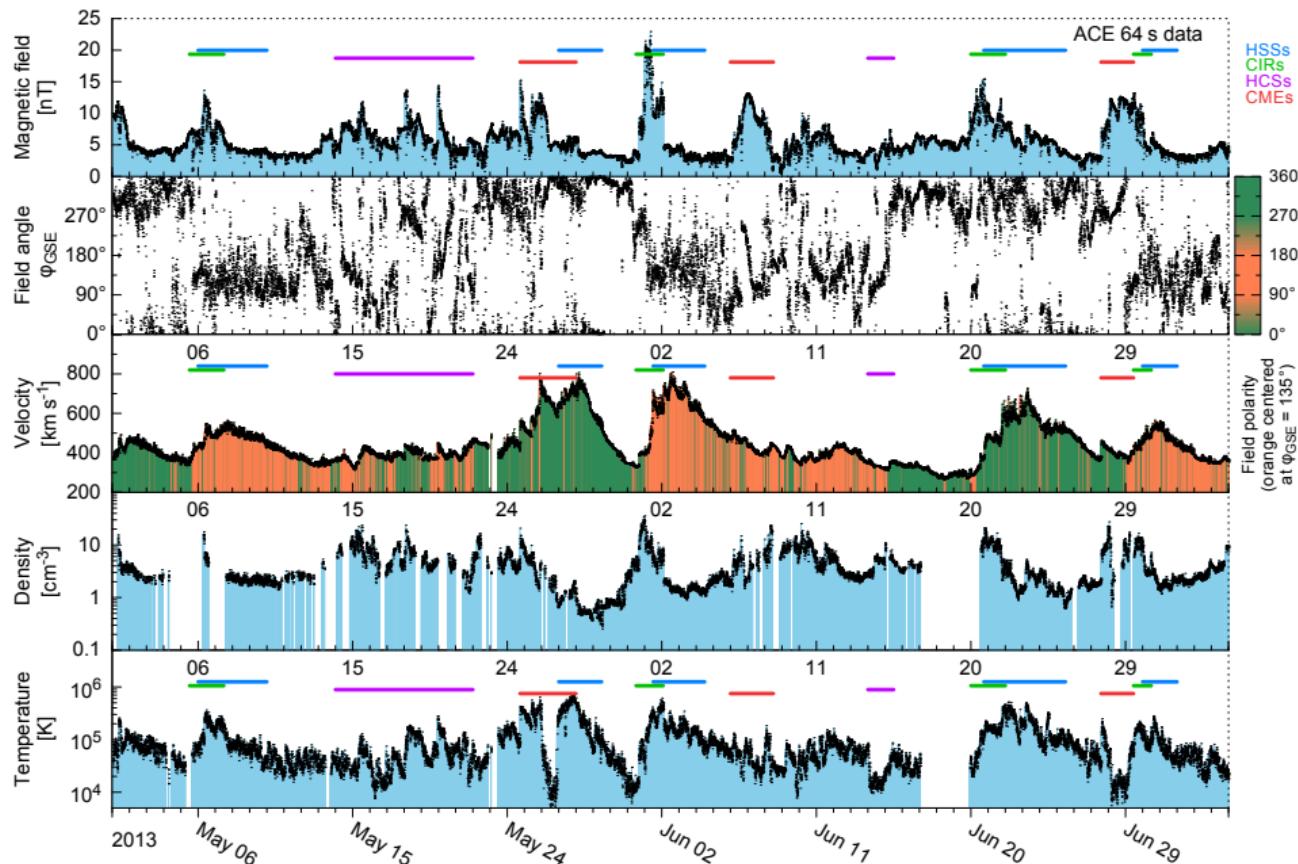
Solar wind data

OMNI data set (King & Papitashvili, 2005)

- intercalibrated multi-spacecraft data
- time-shifted to the bow shock of the magnetosphere
- hourly data since 1963



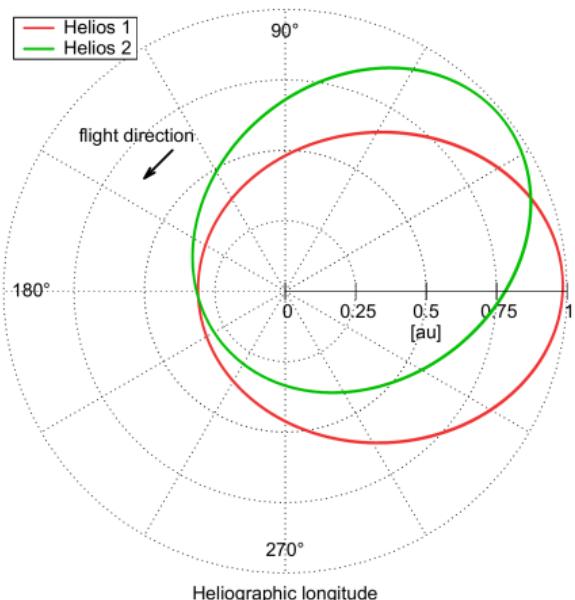
Solar wind



Solar wind data

Helios data set (Rosenbauer et al., 1977)

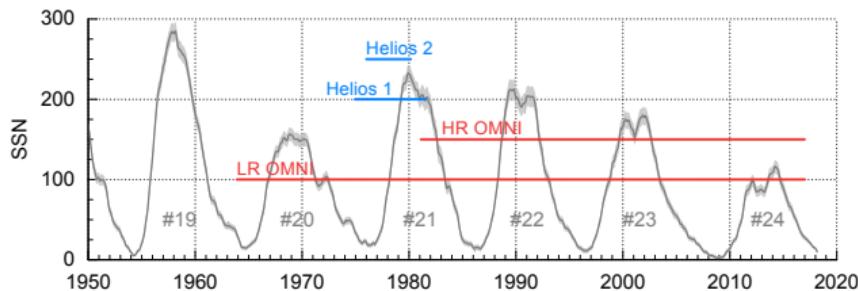
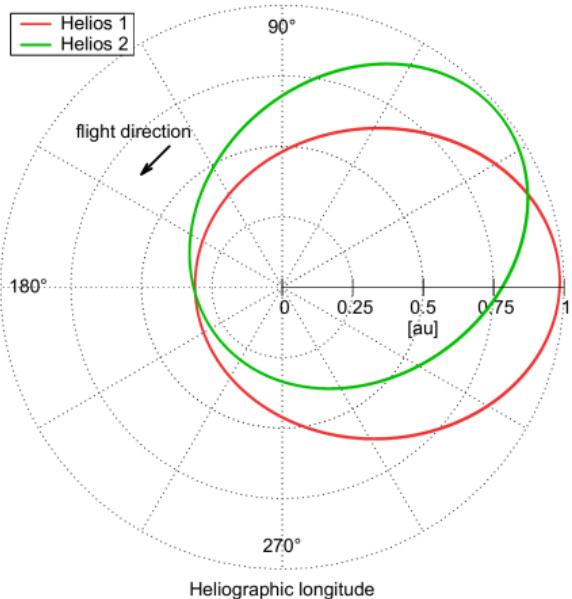
- Helios 1 and Helios 2 probes
- solar distance range 0.29–0.98 au
- hourly data from 1974–1981



Solar wind data

Helios data set (Rosenbauer et al., 1977)

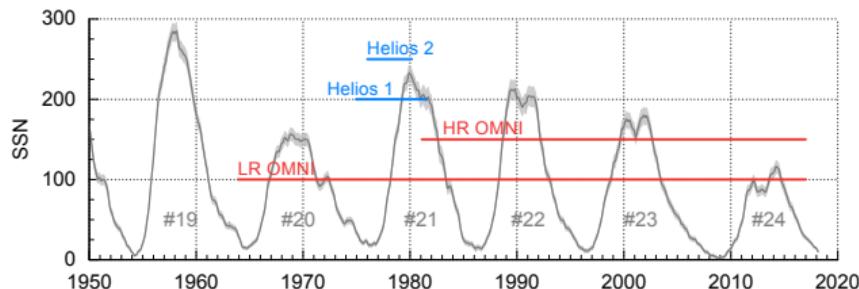
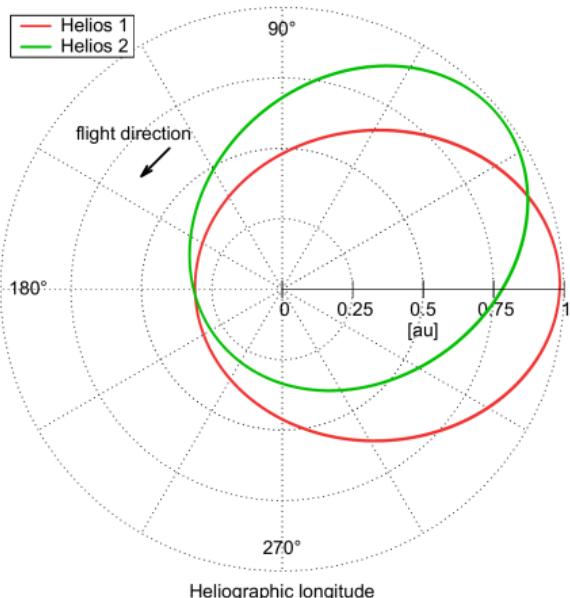
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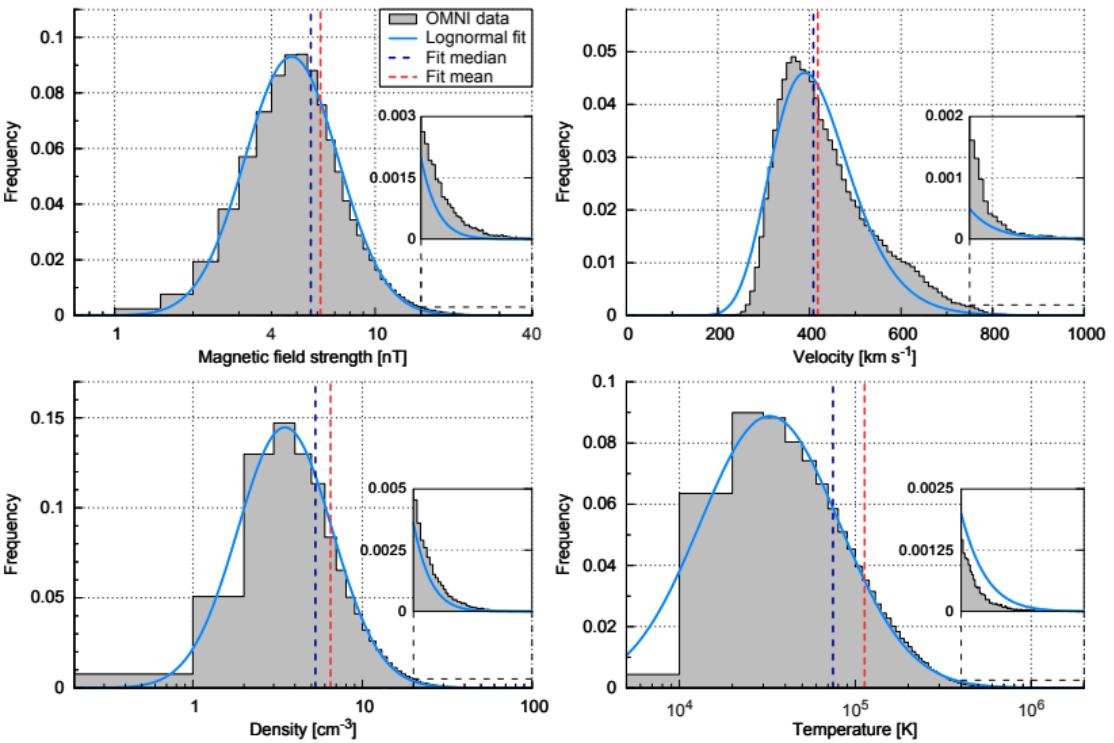


Solar wind model data use

- 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

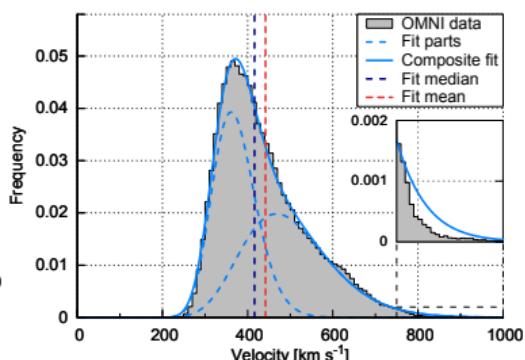
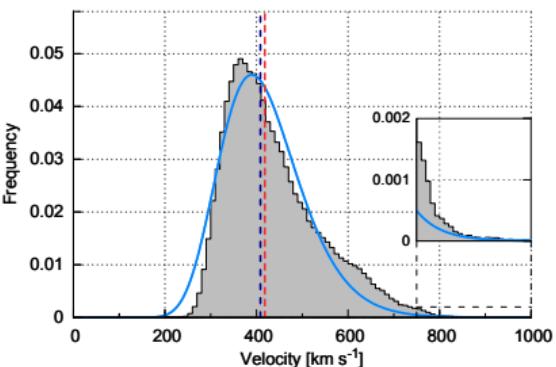
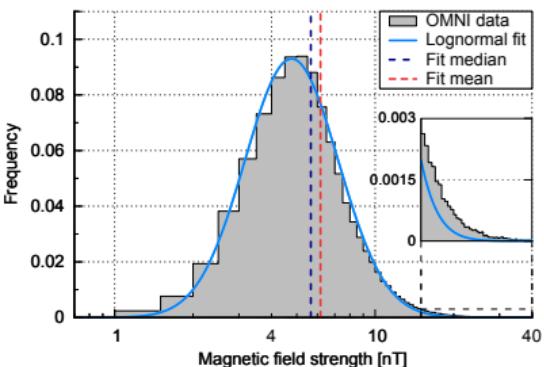
Hourly OMNI data from 1963 to 2016



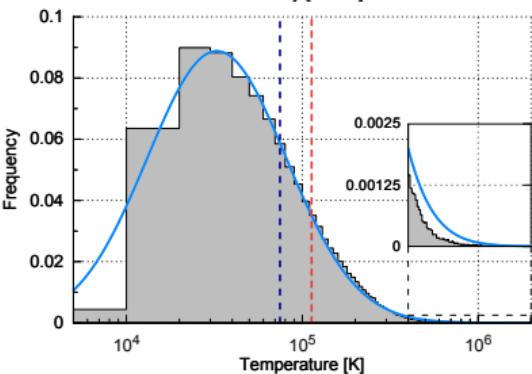
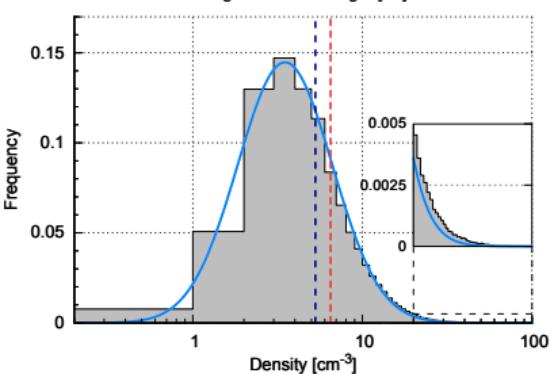
Credit: Venzmer & Bothmer (2018)

Frequency distributions – OMNI data

Hourly OMNI data from 1963 to 2016



Credit: Venzmer & Bothmer (2018)

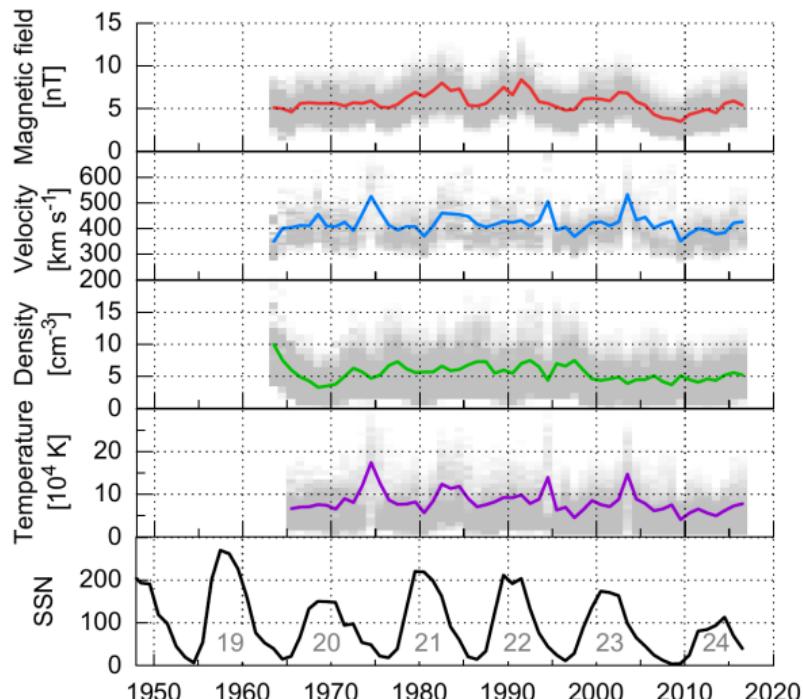


Credit: Venzmer & Bothmer (2018)

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

Solar activity dependence – OMNI data

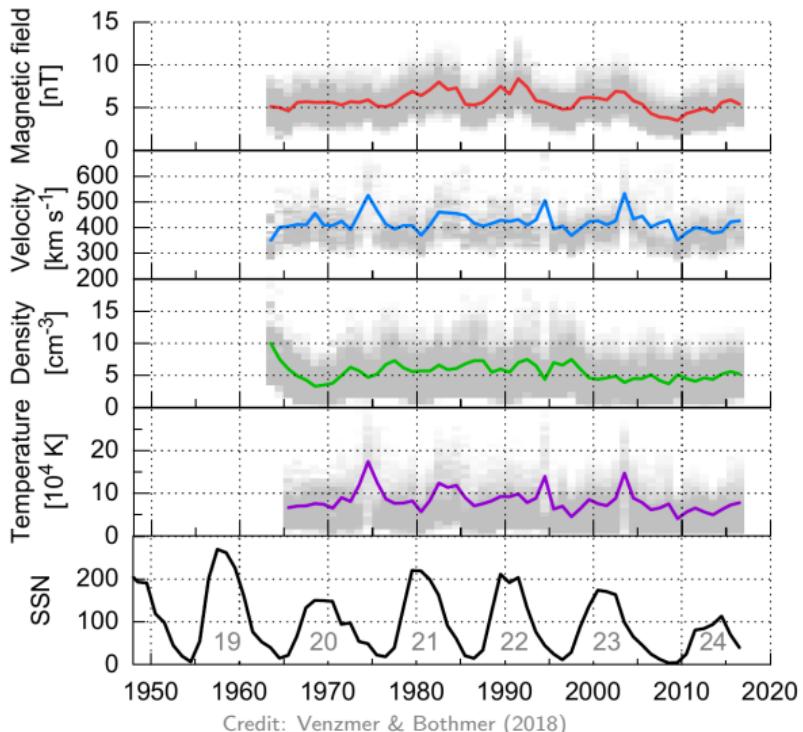
Yearly median values:



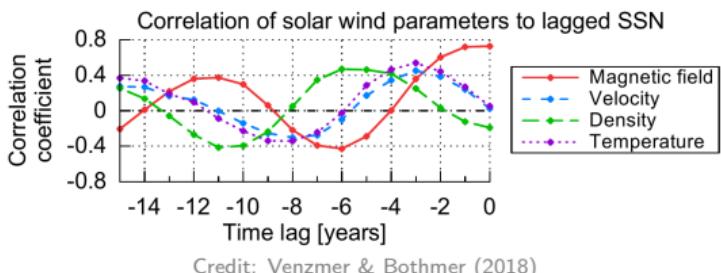
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Solar activity dependence – OMNI data

Yearly median values:



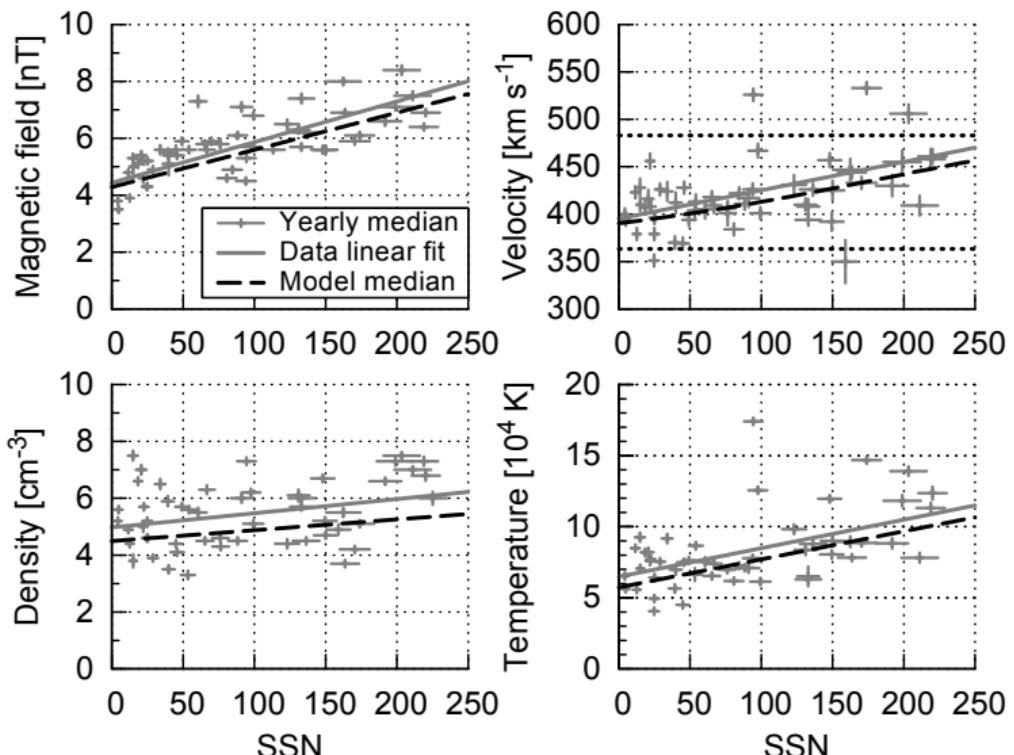
Find time lag with highest correlation coefficient:



Credit: Venzmer & Bothmer (2018)

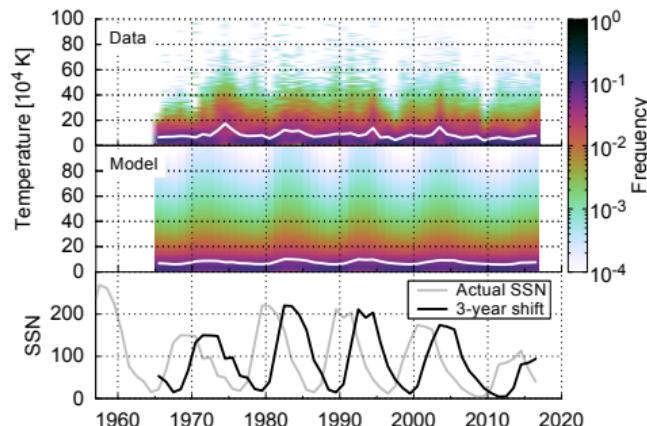
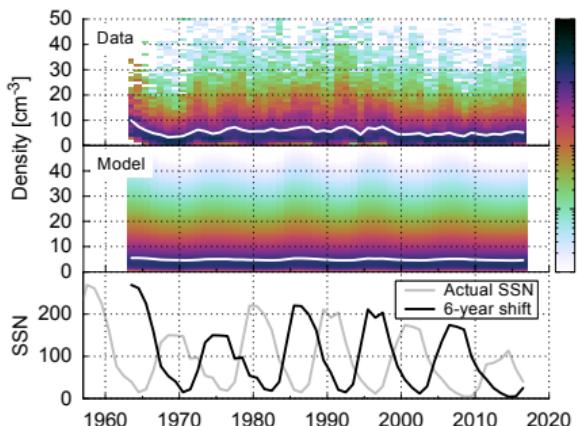
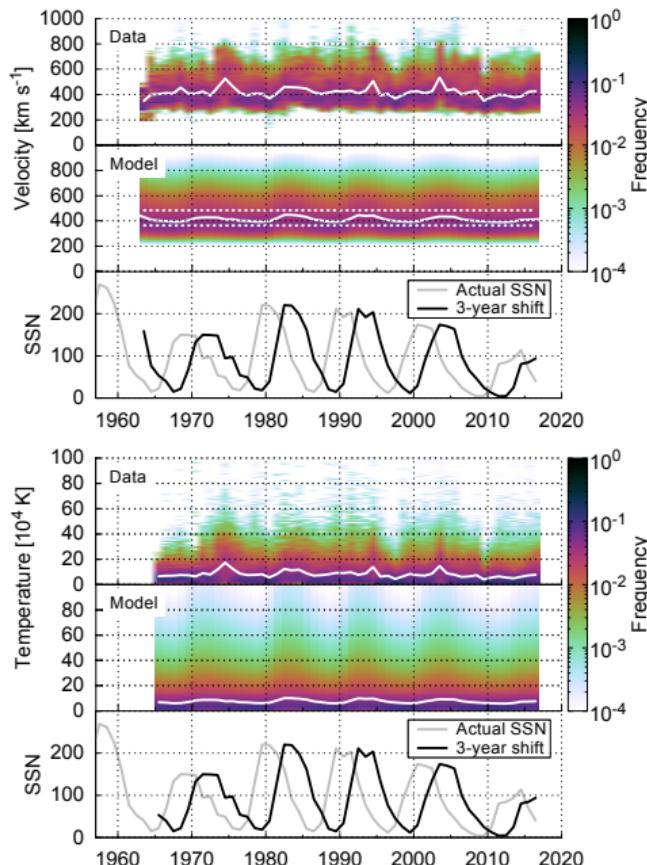
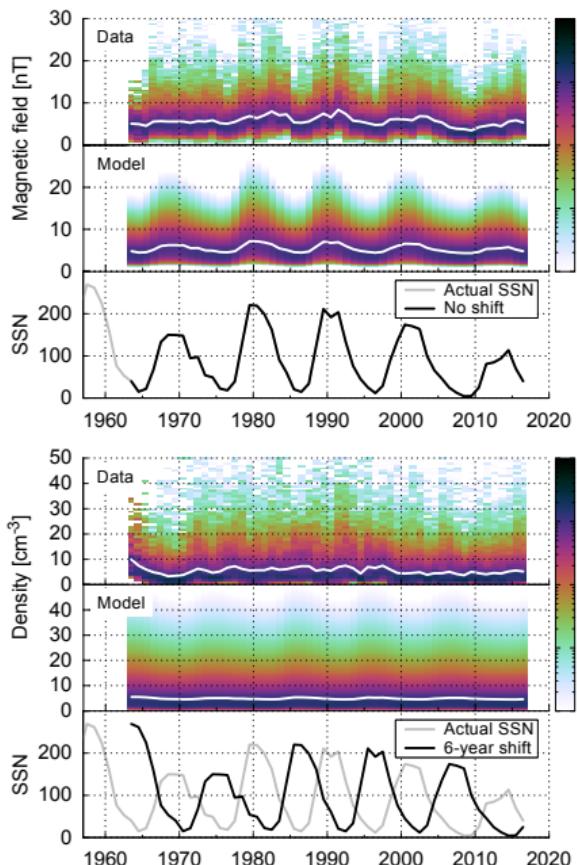
Solar activity dependence – OMNI data

Linear relations with the shifted SSN:



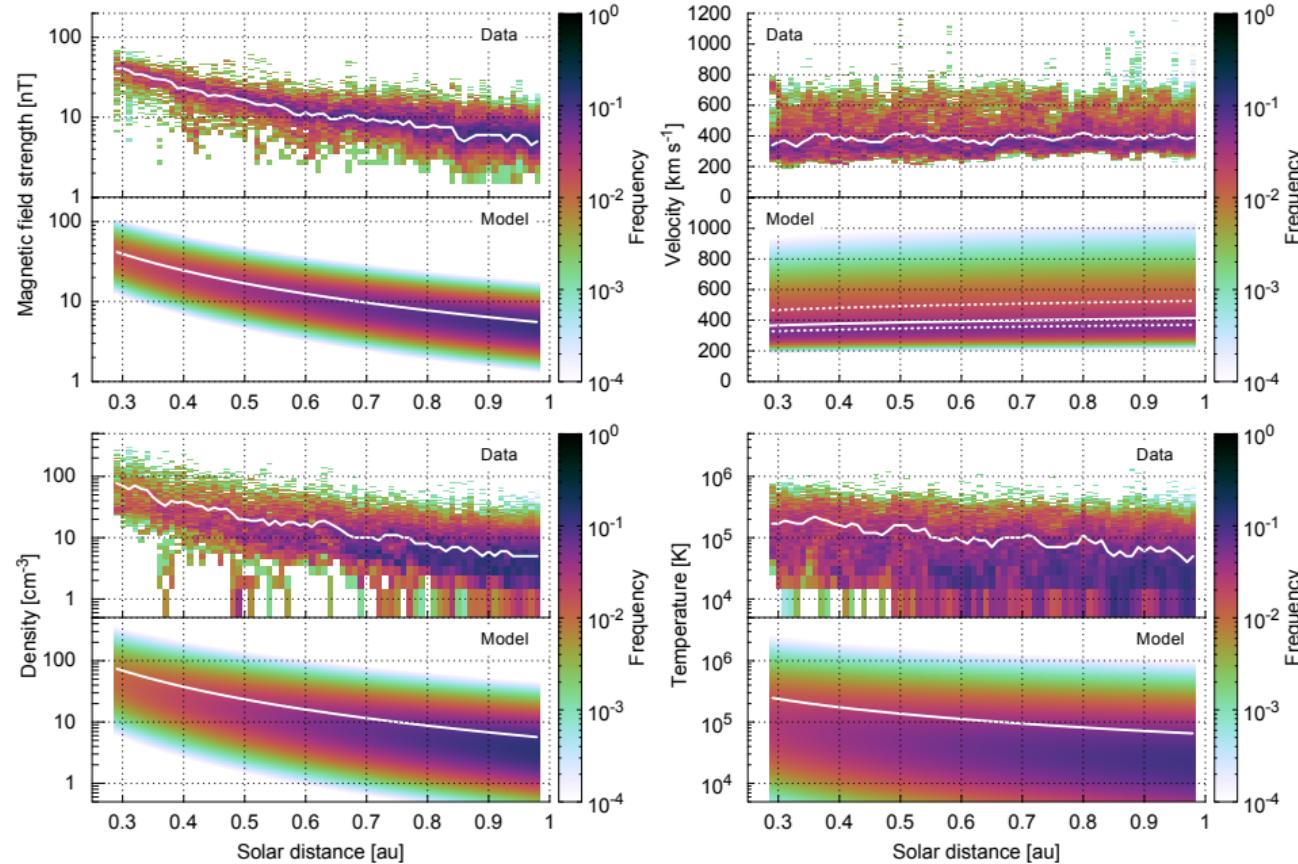
Credit: Venzmer & Bothmer (2018)

Solar activity dependence – OMNI 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
 $x_{\text{med}}(\text{ssn}, r), x_{\text{avg}}(\text{ssn}, r)$
- solar activity relations
 $\text{ssn}(t + t_{\text{lag}})$
- solar distance relations
 $r(t)$

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- 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 relations
 $ssn(t + t_{\text{lag}})$
- solar distance relations
 $r(t)$

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

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

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

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

Density

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

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

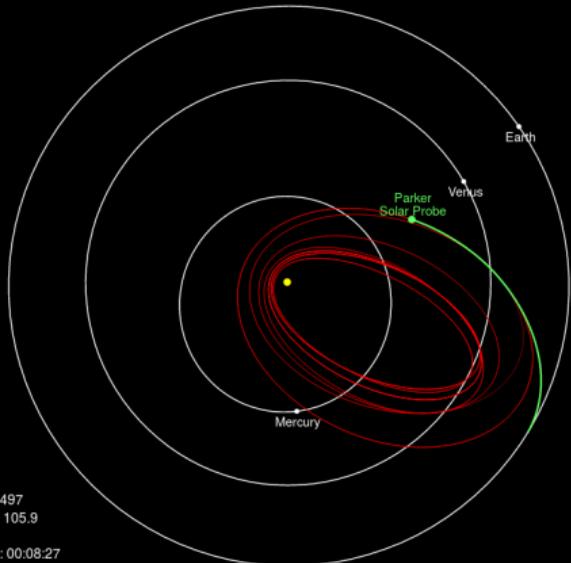
Temperature

$$T_{\text{med}}(ssn, r) = (197 \text{ K} \cdot ssn + 5.73 \times 10^4 \text{ K}) \cdot r^{-1.10}$$

$$T_{\text{avg}}(ssn, r) = 1.654 \cdot T_{\text{med}}(ssn, r)$$

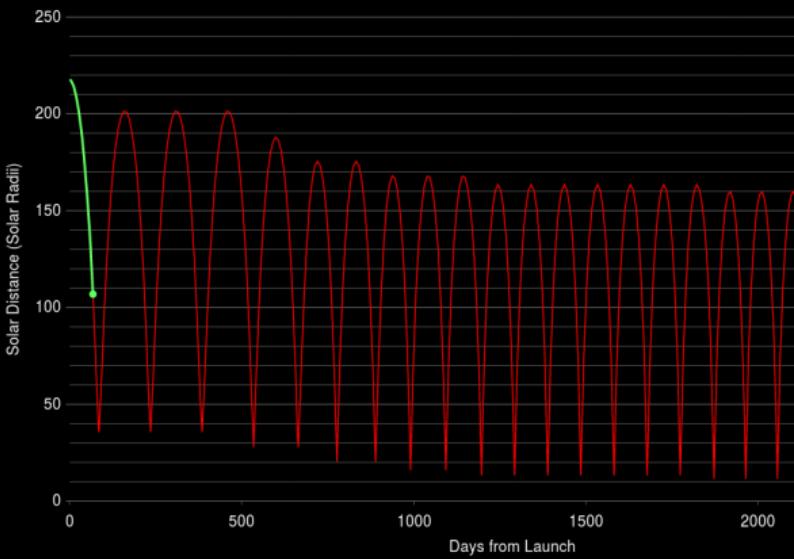
Prediction for PSP orbit

Parker Solar Probe Mission Trajectory and Current Position



Credit: NASA

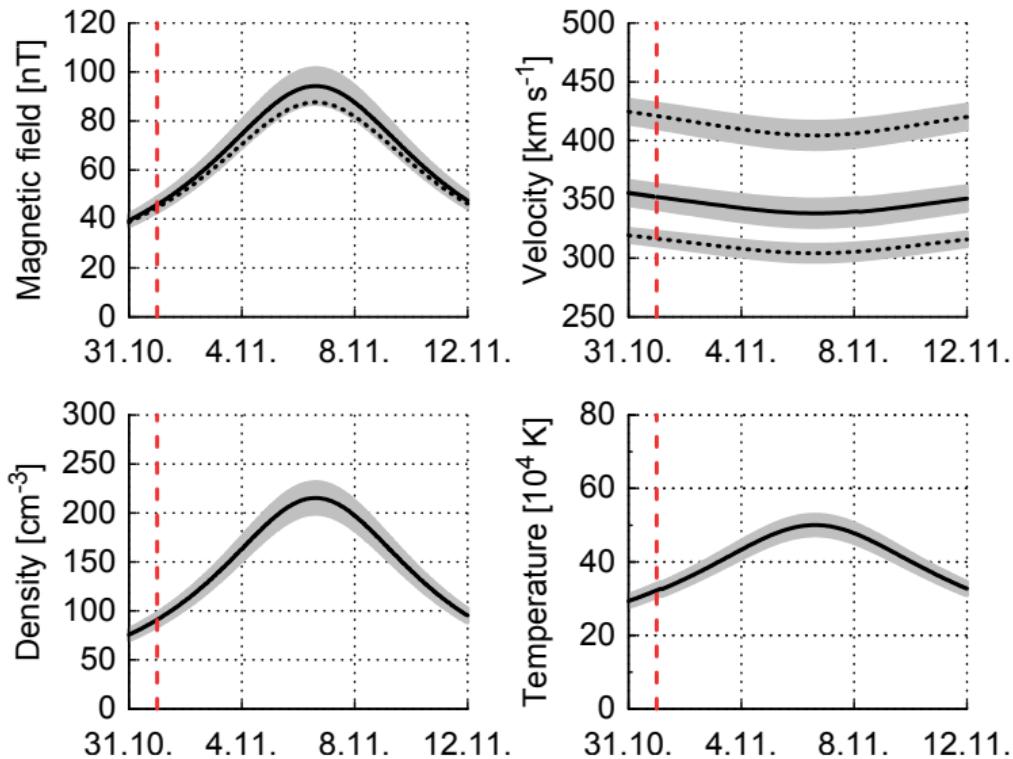
Parker Solar Probe Distance from Sun



- ⇒ Extrapolate the model in distance
- ⇒ Feed the model with SSN predictions

Prediction for PSP orbit

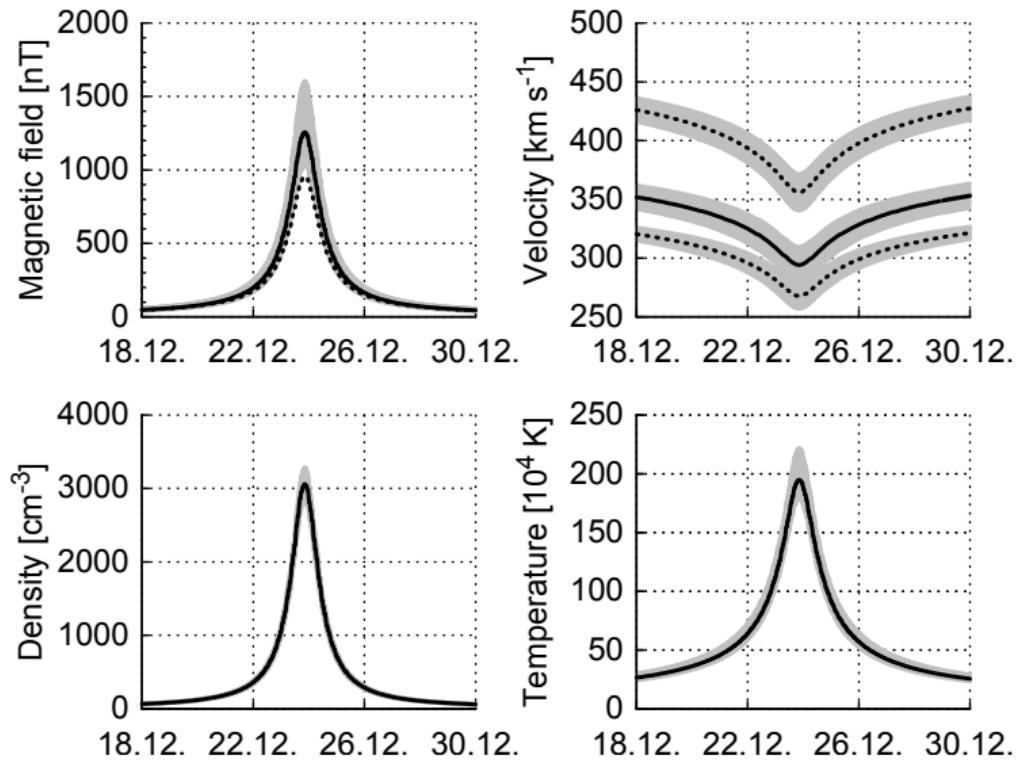
Perihelion #1 at $36.7 R_{\odot}$



November 2018

Prediction for PSP orbit

Perihelion #22 at $9.86 R_{\odot}$



Comparison with other studies

Predicted values at $9.86 R_{\odot}$

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

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

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

$$T = 1.93 \times 10^6 \text{ K}$$

Comparison with other studies

Predicted values at $9.86 R_{\odot}$

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

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

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

$$T = 1.93 \times 10^6 \text{ K}$$

- Magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)

Comparison with other studies

Predicted values at $9.86 R_{\odot}$

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

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

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

$$T = 1.93 \times 10^6 \text{ K}$$

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Extrapolation results (Venzmer & Bothmer, 2018)

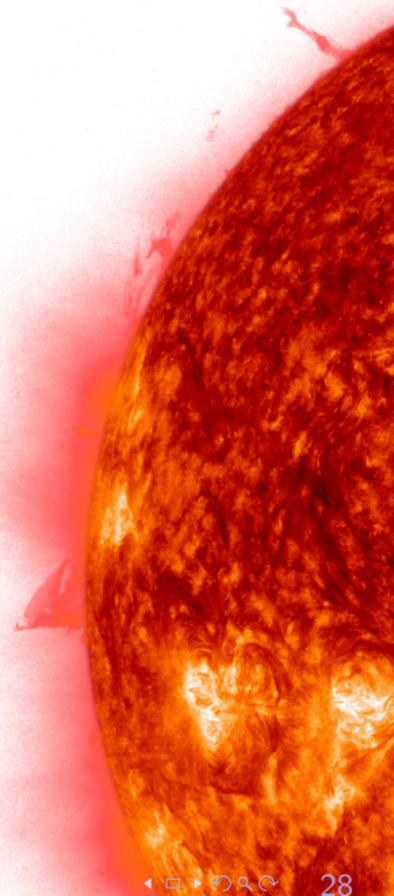
- Remote observations show the limits of the extrapolation
- Velocity and temperature are overestimated
- Solar wind is still being heated and accelerated in this region (up to $20 R_{\odot}$)

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



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Thank you!

References |

- Banaszkiewicz, M., Axford, W. I. & McKenzie, J. F. 1998, *An analytic solar magnetic field model*, Astron. Astrophys., 337, 940, [ADS].
- Billings, D. E. 1959, *Distribution of Matter with Temperature in the Emission Corona.*, Astrophys. J., 130, 961, [DOI], [ADS].
- Bothmer, V. & Schwenn, R. 1998, *The structure and origin of magnetic clouds in the solar wind*, Annales Geophysicae, 16, 1, [DOI], [ADS].
- Cranmer, S. R. & van Ballegooijen, A. A. 2005, *On the Generation, Propagation, and Reflection of Alfvén Waves from the Solar Photosphere to the Distant Heliosphere*, Astrophys. J., Suppl. Ser., 156, 265, [DOI], [ADS].
- Davies, K. 1990, *Ionospheric Radio* (Institution of Engineering and Technology), [link], [DOI].
- Fox, N. J., Velli, M. C., Bale, S. D. et al. 2015, *The Solar Probe Plus Mission: Humanity's First Visit to Our Star*, Space Sci. Rev., [DOI], [ADS].
- Hathaway, D. H. 2015, *The Solar Cycle*, Living Reviews in Solar Physics, 12, 4, [DOI], [ADS].
- Hughes, W. J. 1995, *Chapter 9: The magnetopause, magnetotail, and magnetic reconnection*, ed. M. Kivelson & C. Russell, Introduction to Space Physics (Cambridge University Press, Cambridge), 227–287, [ADS].
- Leblanc, Y., Dulk, G. A., & Bougeret, J.-L. 1998, Solar Phys., 183, 165
- Liebenberg, D. H., Bessey, R. J. & Watson, B. 1975, *Coronal emission line profile observations at total solar eclipses. II - 30 May 1965 results, deconvolution and interpretation*, Solar Phys., 44, 345, [DOI], [ADS].
- King, J. H. & Papitashvili, N. E. 2005, *Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data*, Journal of Geophysical Research (Space Physics), 110, 2104, [DOI], [ADS].
- Marubashi, K. & Lepping, R. P. 2007, *Long-duration magnetic clouds: a comparison of analyses using torus- and cylinder-shaped flux rope models*, Annales Geophysicae, 25, 2453, [DOI], [ADS].
- McComas, D. J., Ebert, R. W., Elliott, H. A. et al. 2008a, *Weaker solar wind from the polar coronal holes and the whole Sun*, Geophys. Res. Lett., 35, L18103, [DOI], [ADS].
- Owens, M. J. & Forsyth, R. J. 2013, *The Heliospheric Magnetic Field*, Living Reviews in Solar Physics, 10, 5, [DOI], [ADS].
- Parker, E. N. 1958, *Dynamics of the Interplanetary Gas and Magnetic Fields.*, Astrophys. J., 128, 664, [DOI], [ADS].
- Pizzo, V. J. 1991, *The evolution of corotating stream fronts near the ecliptic plane in the inner solar system. II - Three-dimensional tilted-dipole fronts*, J. Geophys. Res., 96, 5405, [DOI], [ADS].

References II

- Rosenbauer, H., Schwenn, R., Marsch, E. et al. 1977, *A survey on initial results of the HELIOS plasma experiment*, Journal of Geophysics Zeitschrift Geophysik, 42, 561, [ADS].
- Schatten, K. H., Wilcox, J. M. & Ness, N. F. 1969, *A model of interplanetary and coronal magnetic fields*, Solar Phys., 6, 442, [DOI], [ADS].
- Sheeley, N. R., Wang, Y.-M., Hawley, S. H., et al. 1997, *Astrophys. J.*, 484, 472
- Venzmer, M. S. & Bothmer, V. 2018, *Solar-wind predictions for the Parker Solar Probe orbit. Near-Sun extrapolations derived from an empirical solar-wind model based on Helios and OMNI observations*, Astron. Astrophys., 611, A36, [DOI], [ADS].
- Wang, Y.-M., Sheeley, N. R., Socker, D. G., Howard, R. A. & Rich, N. B. 2000, *The dynamical nature of coronal streamers*, J. Geophys. Res., 105, 25133, [DOI], [ADS].

Backup slides



Solar wind

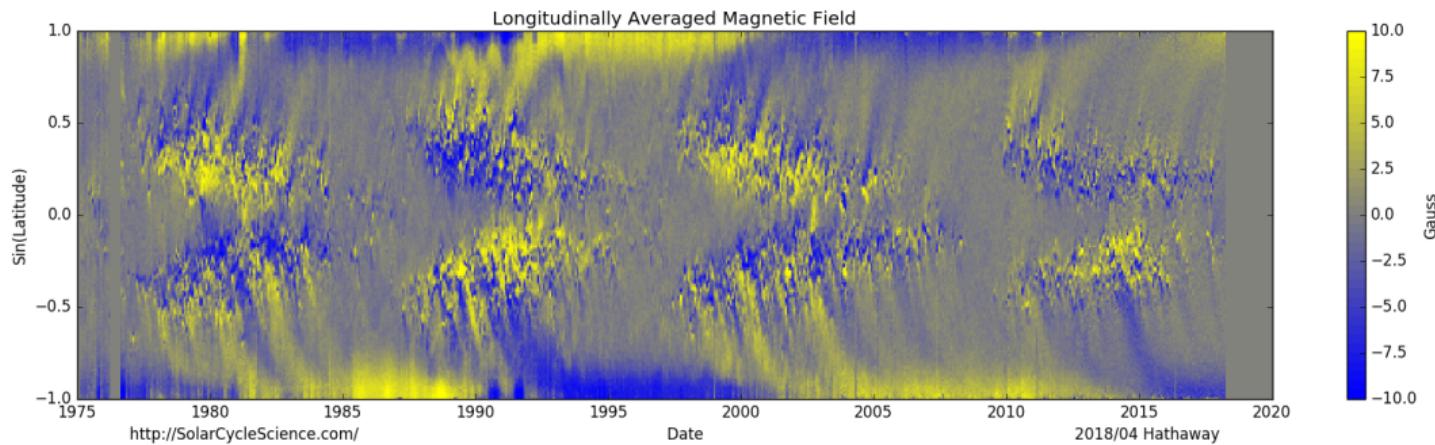
Solar activity

Magnetic butterfly diagram

Geomagnetic impact of the solar wind

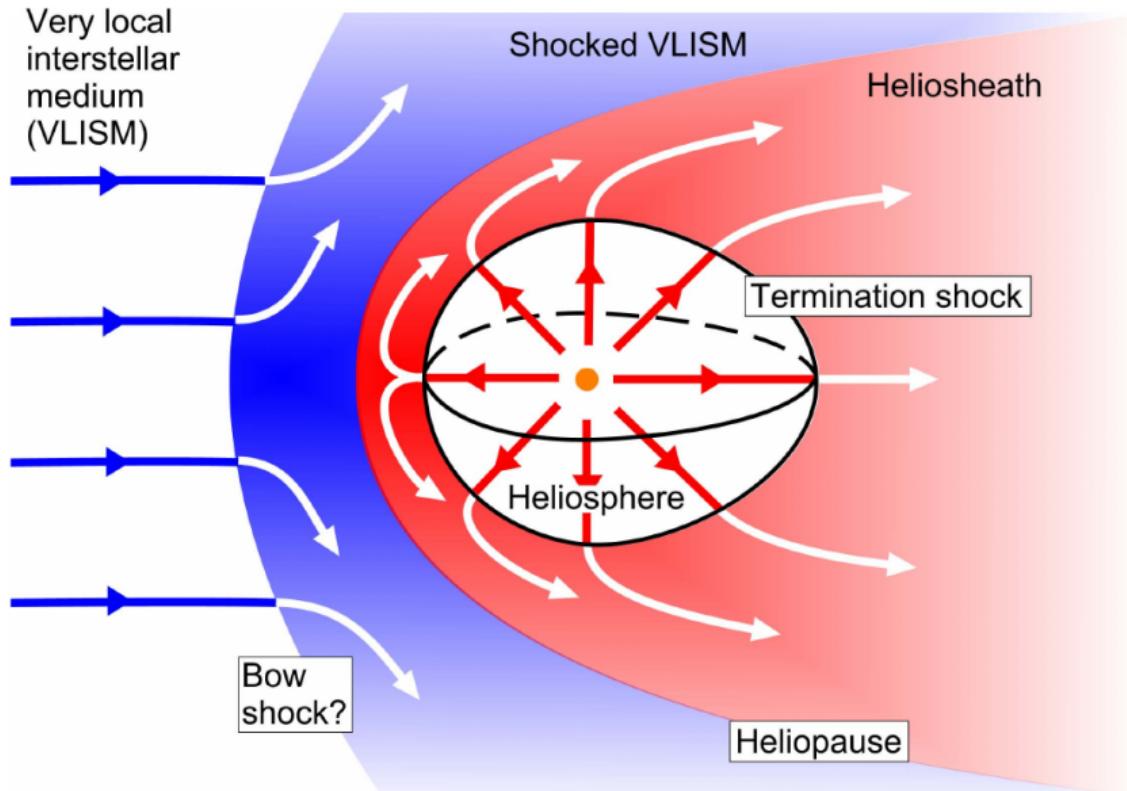


Solar wind model for the inner heliosphere



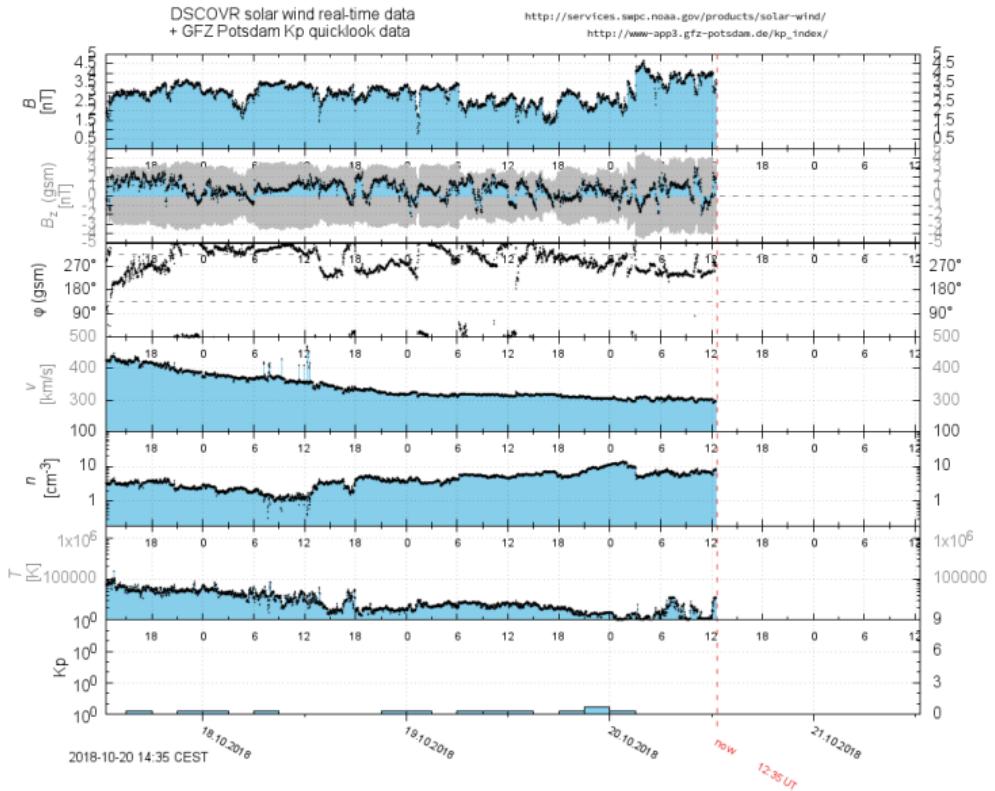
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

Solar wind



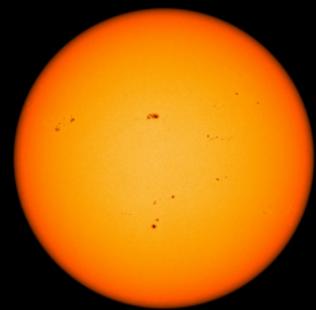
Credit: Owens & Forsyth (2013, Fig. 9)

Solar wind

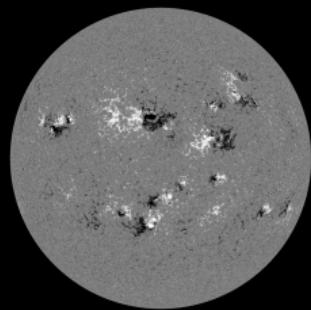


Solar surface and atmosphere

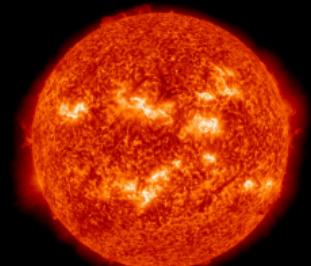
Intensitygram



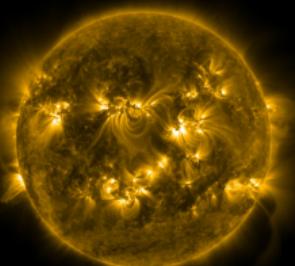
Magnetogram



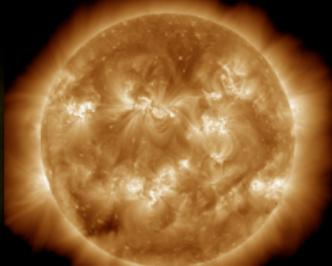
304 Å



171 Å

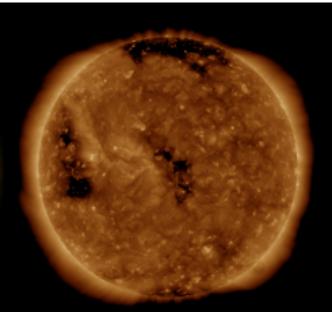
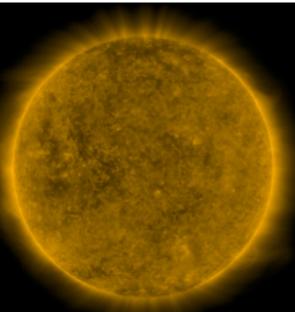
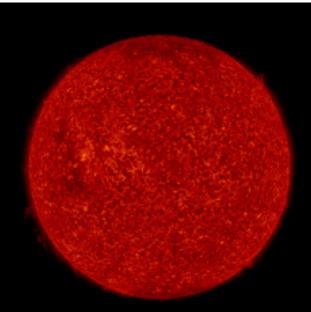
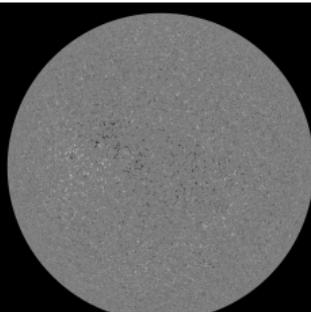
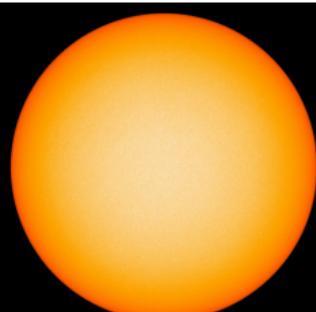


193 Å



Credit: NASA SDO/HMI, 16 May 2013

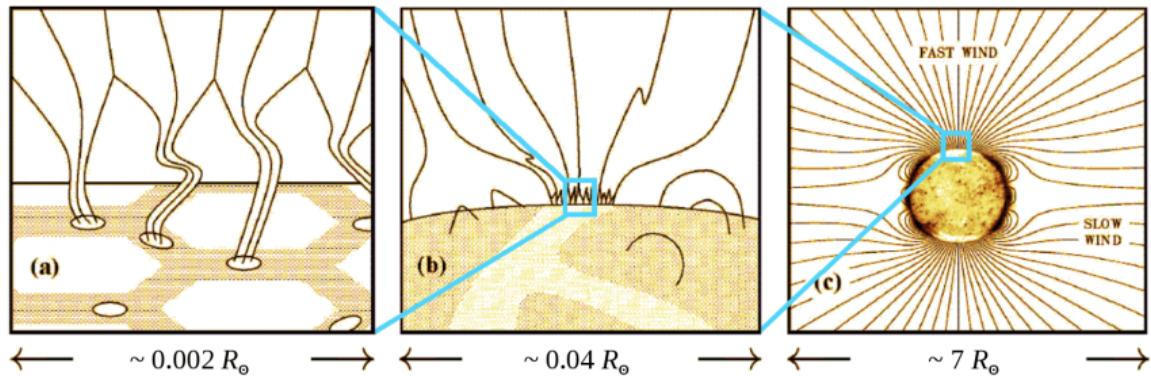
Credit: NASA SDO/AIA, 16 May 2013



Credit: NASA SDO/HMI, 28 October 2018

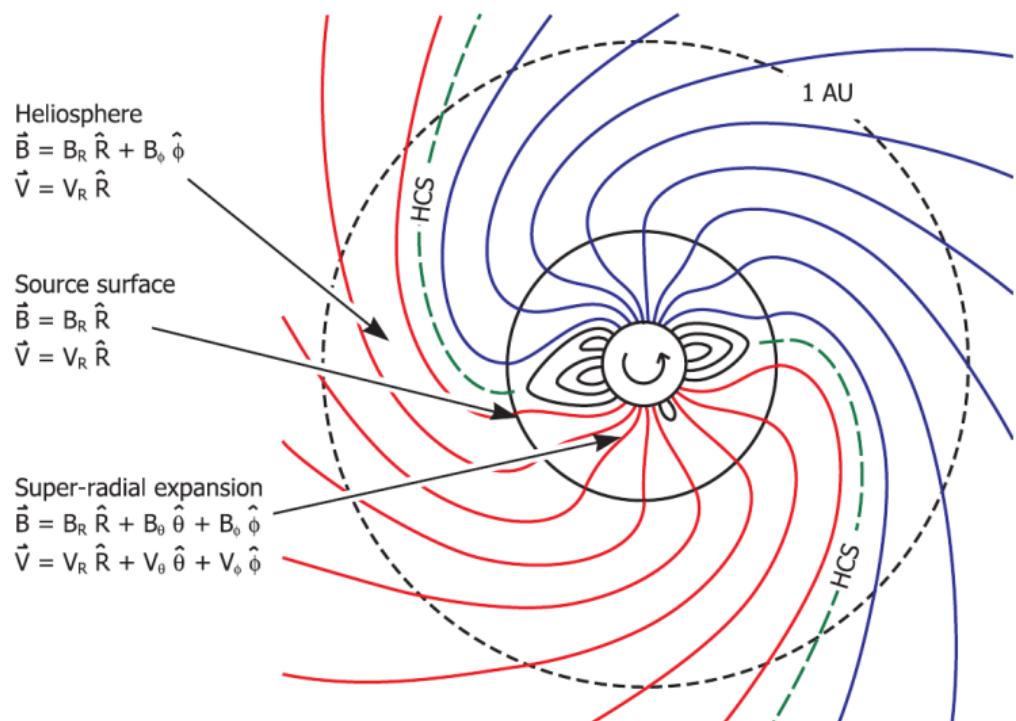
Credit: NASA SDO/AIA, 28 October 2018

Solar magnetic field



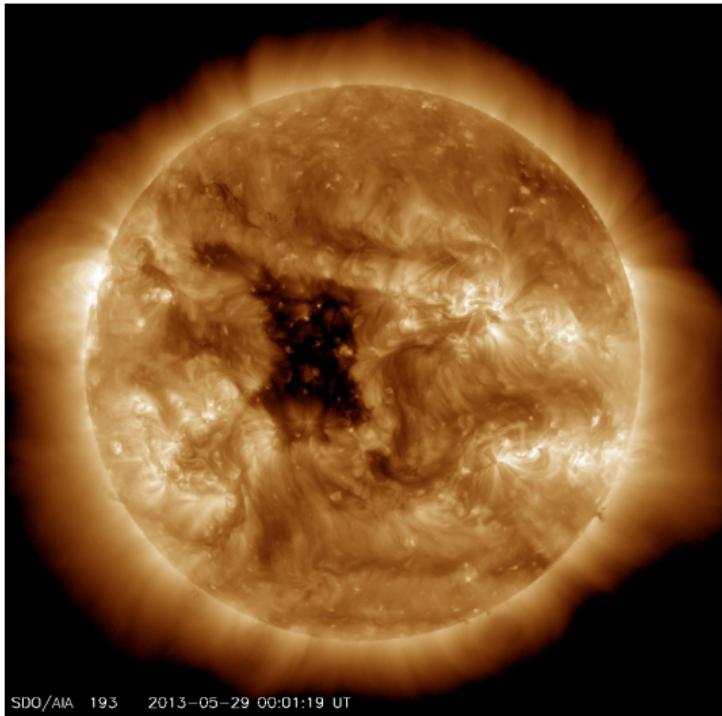
Courtesy of S. R. Cranmer

Solar magnetic field



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

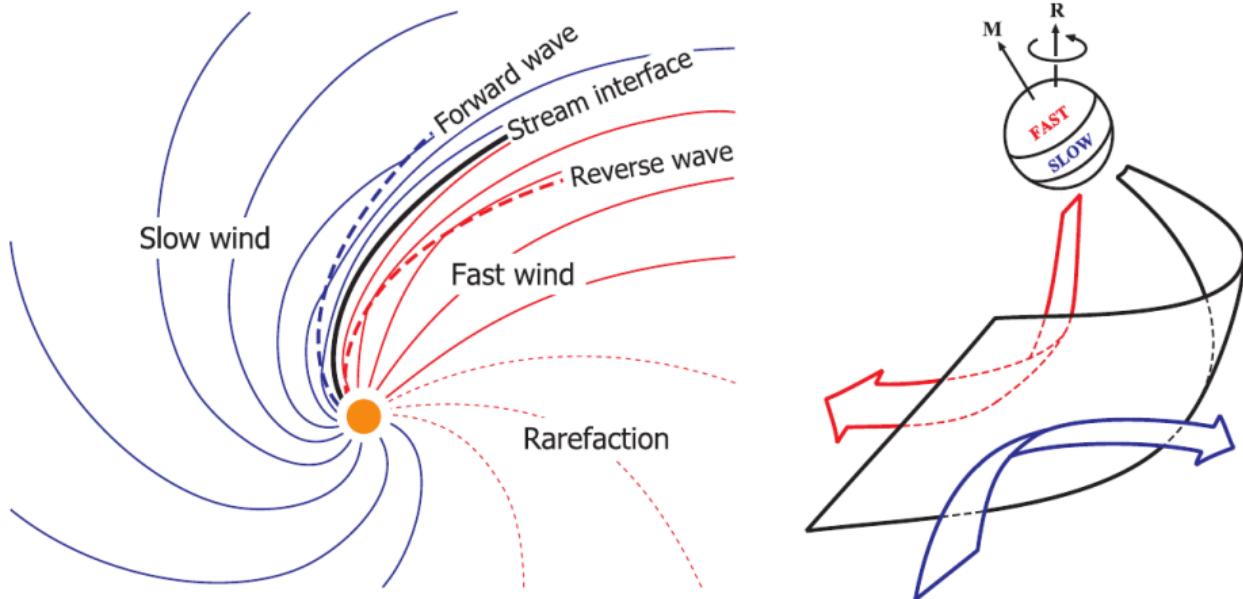
Slow and fast solar wind



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

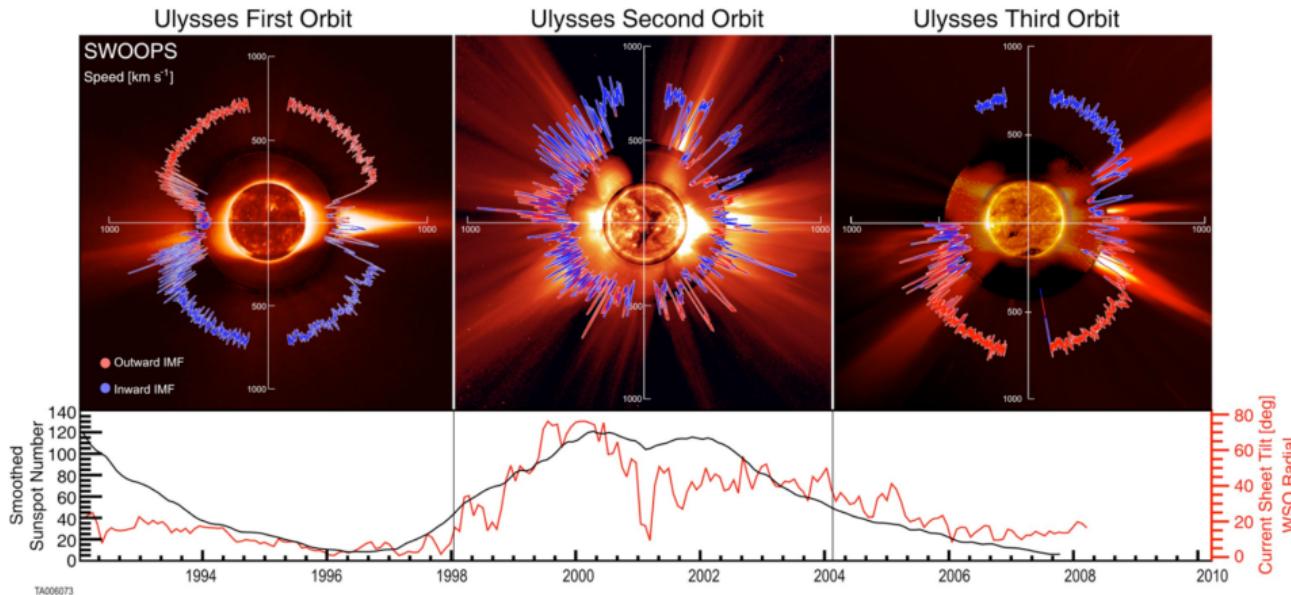
Credit: NASA/SDO and the AIA, EVE and HMI science teams

Slow and fast solar wind



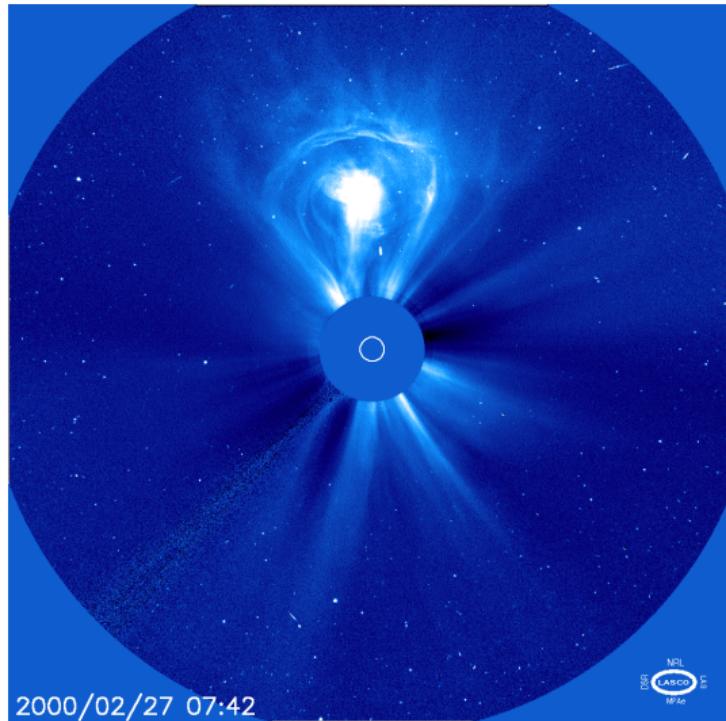
Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

Solar activity



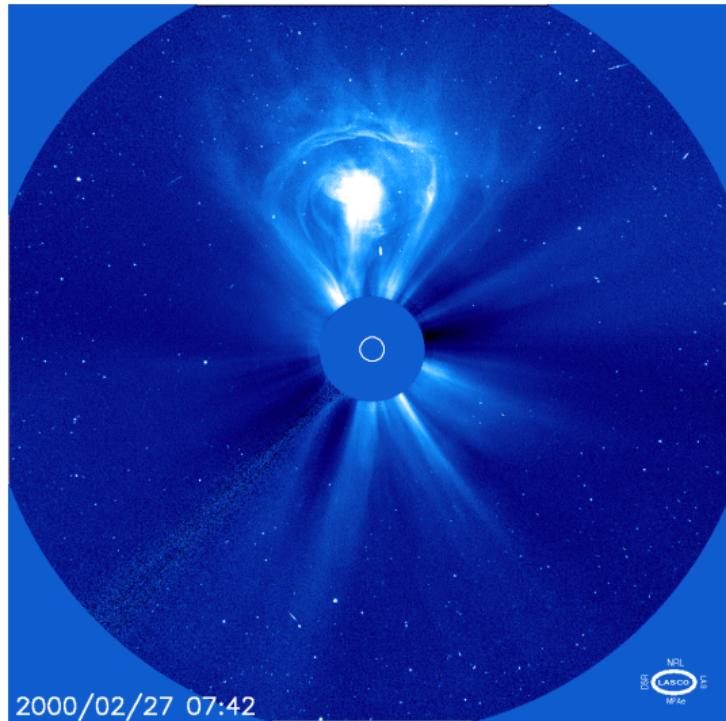
Credit: McComas et al. (2008a, Fig. 1)

Coronal mass ejections

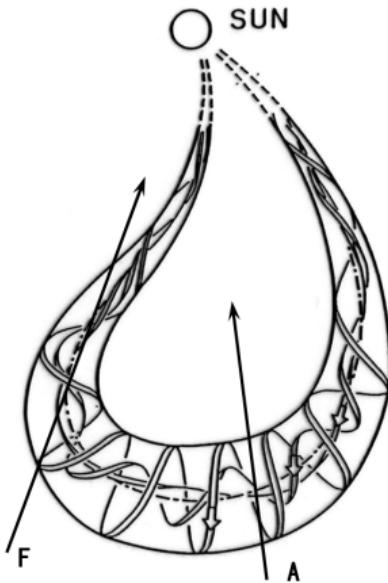


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

Coronal mass ejections

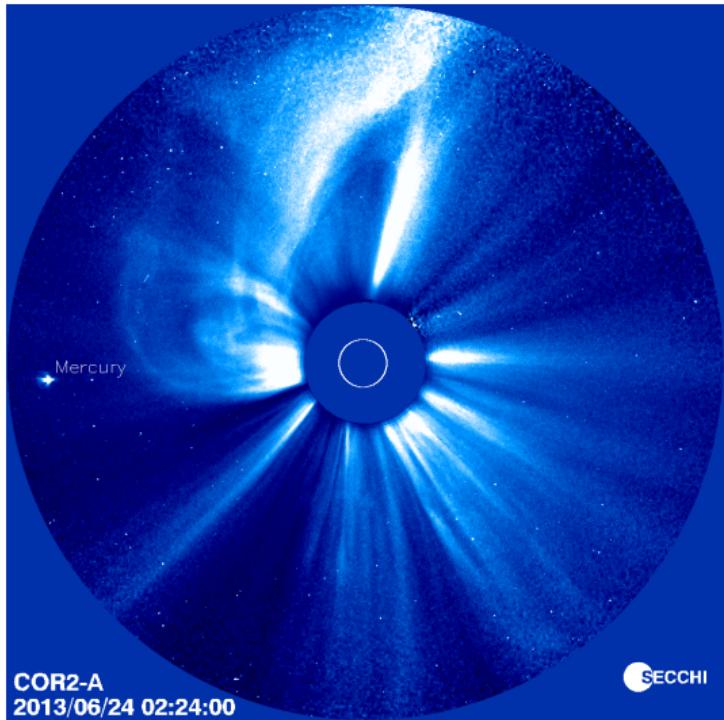


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

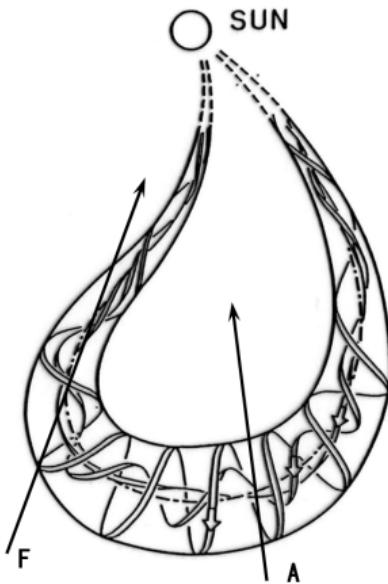


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections

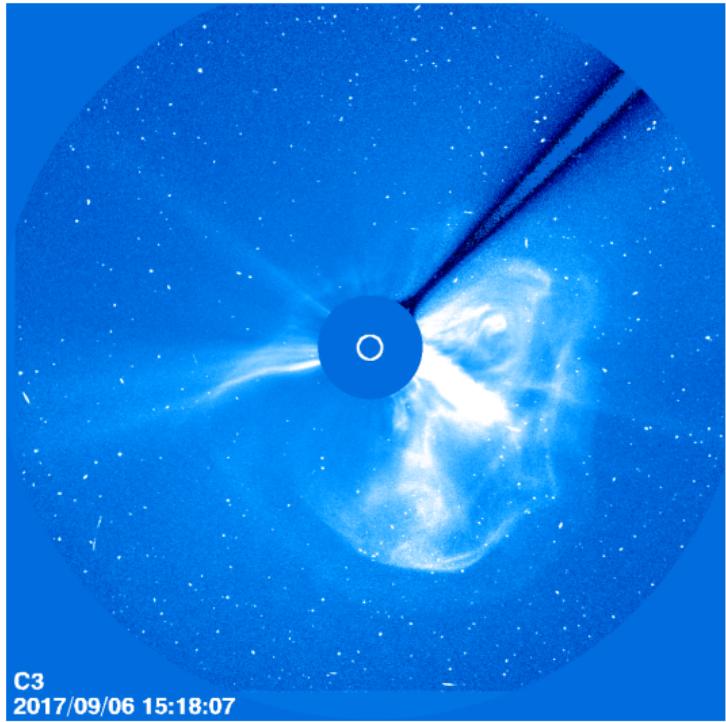


Courtesy of STEREO/COR2 consortium (NASA)



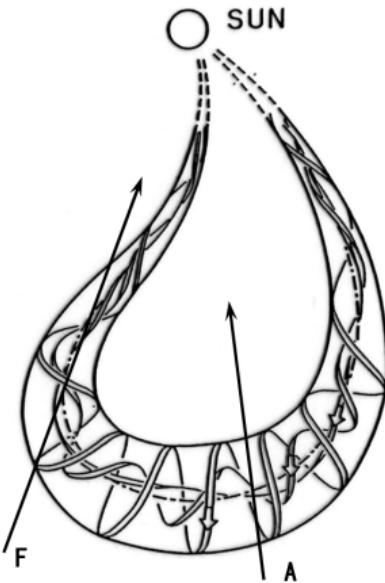
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections



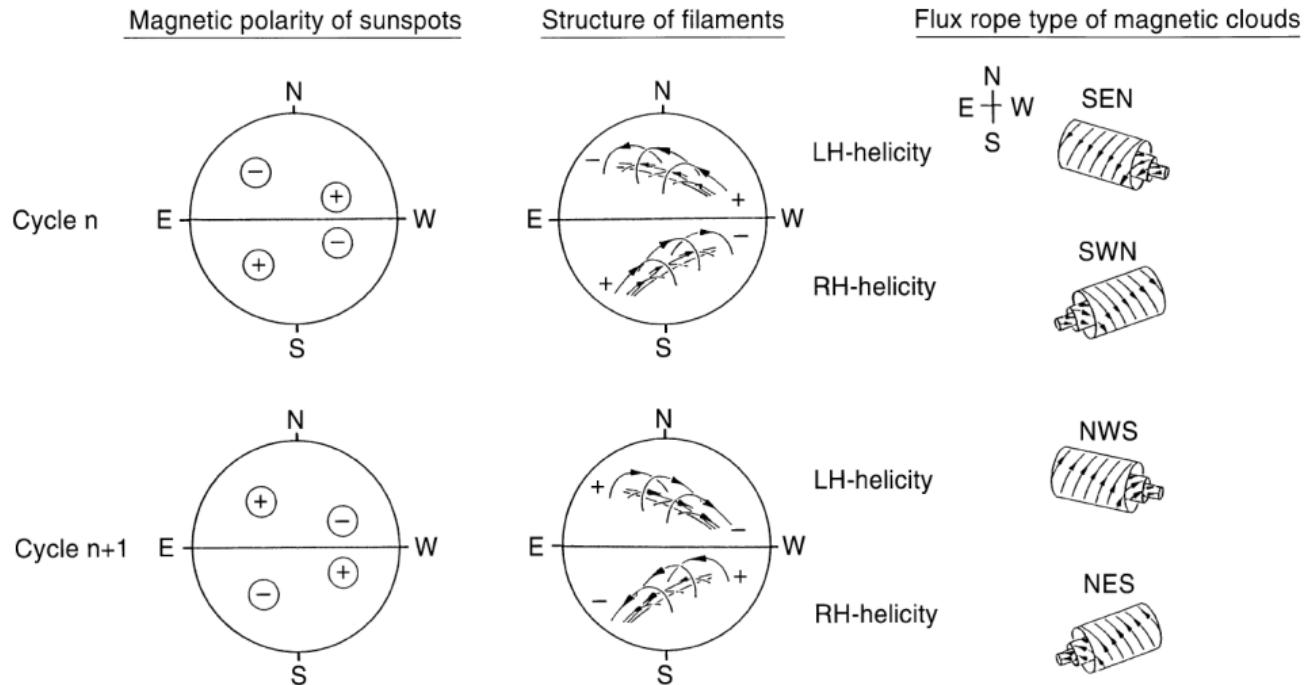
C3
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Courtesy of SOHO/LASCO consortium; SOHO is a project of international cooperation between ESA and NASA



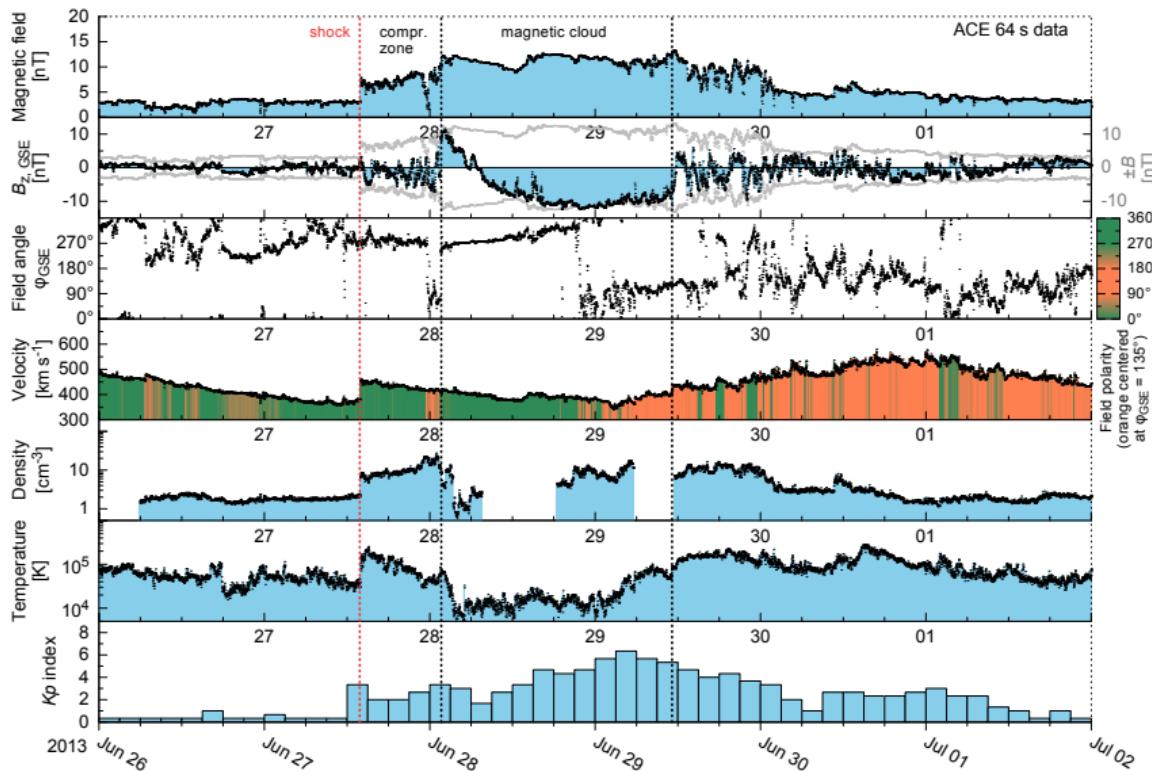
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

CME orientation

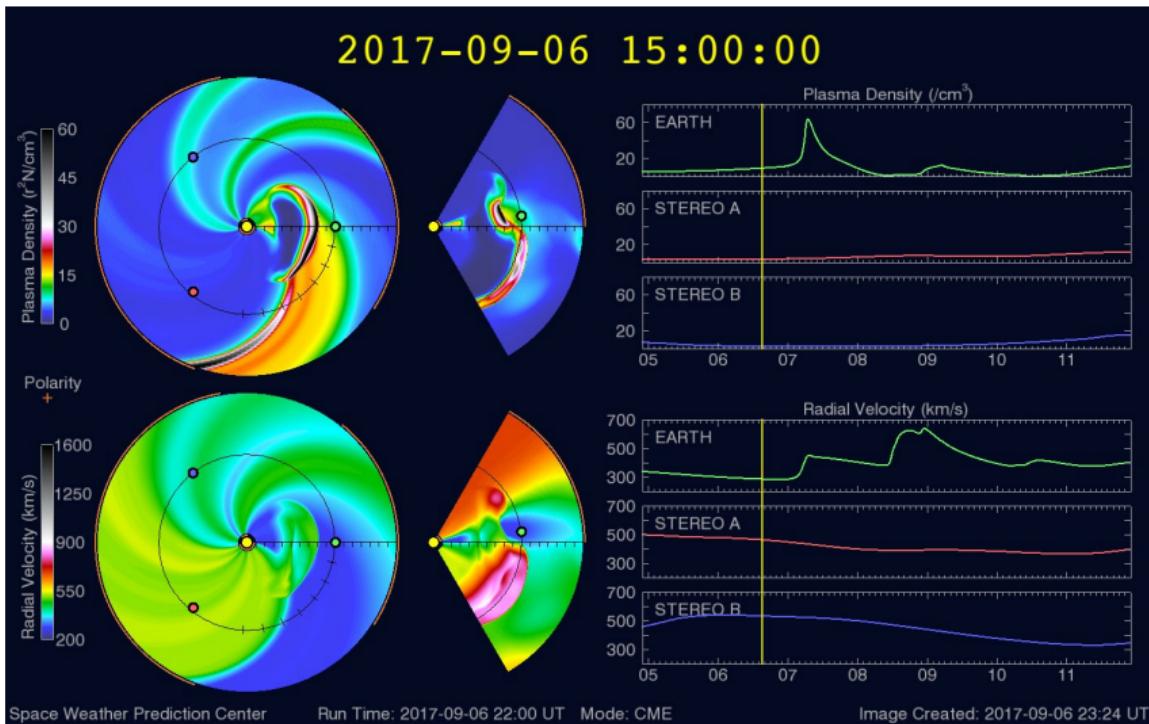


Credit: Bothmer & Schwenn (1998, Fig. 18)

In-situ CMEs

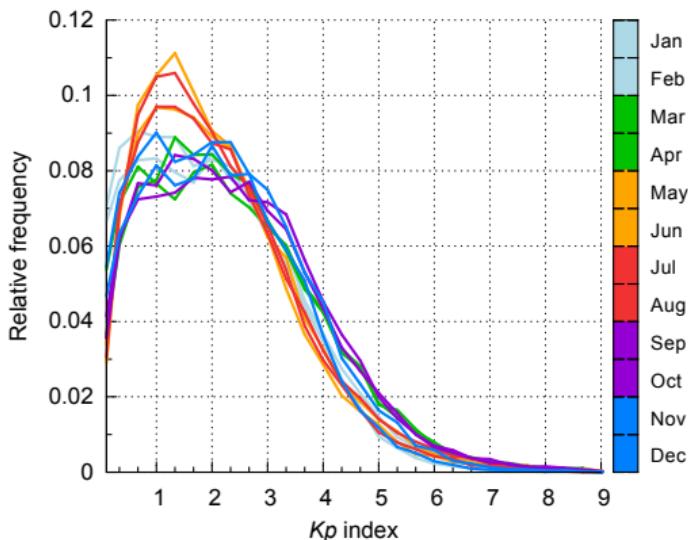
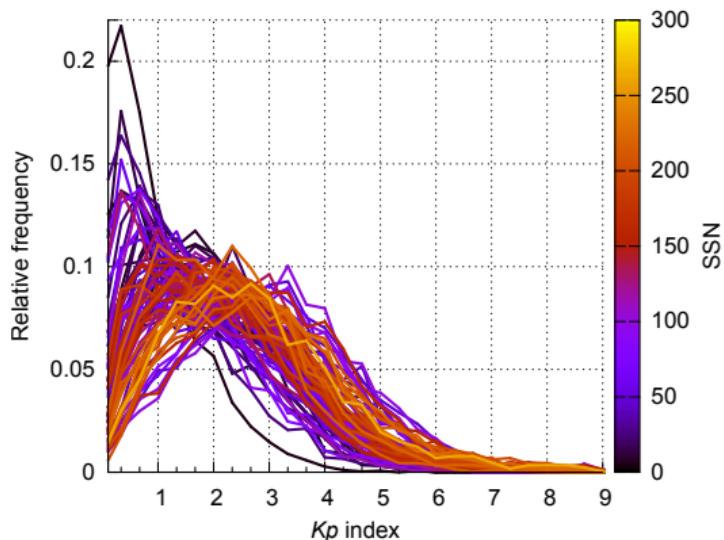


Solar wind and CME forecast

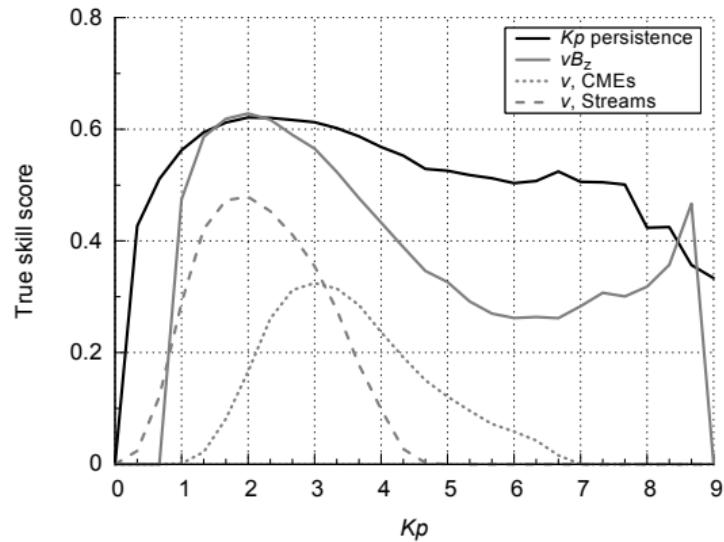
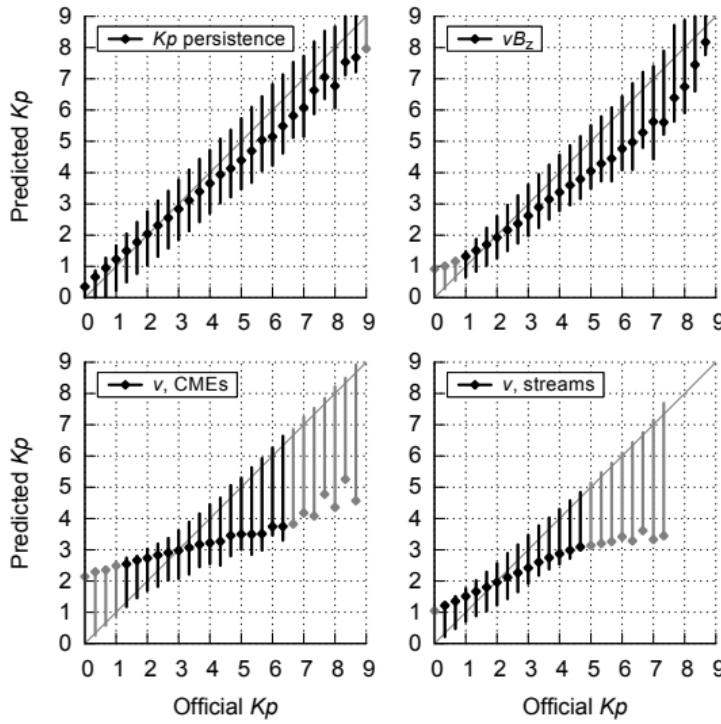


Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

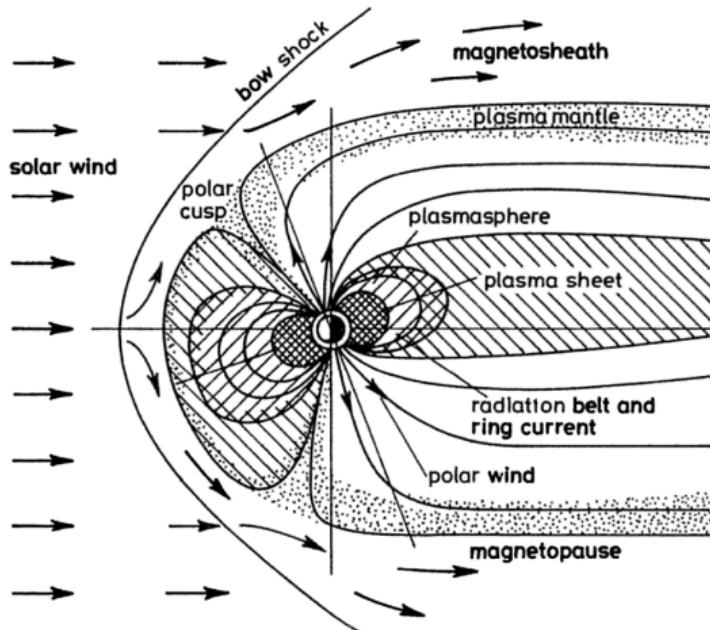
Kp long-term variations



Prediction performance



Magnetosphere

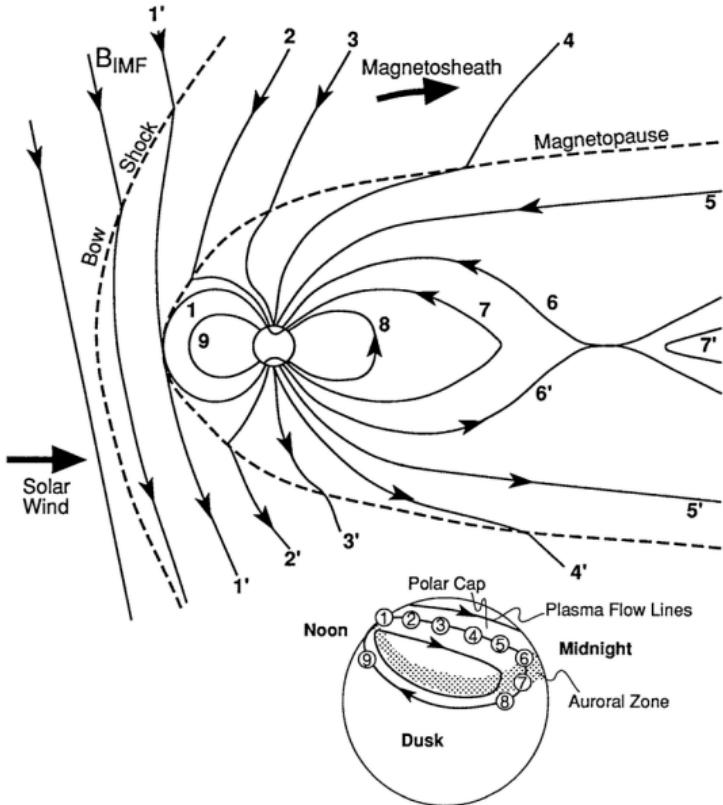


Credit: Davies (1990, Fig. 2.12)

Interaction mechanisms between solar wind and magnetosphere:

- Reconnection
- Turbulence
- Compression
- Induction

Magnetosphere



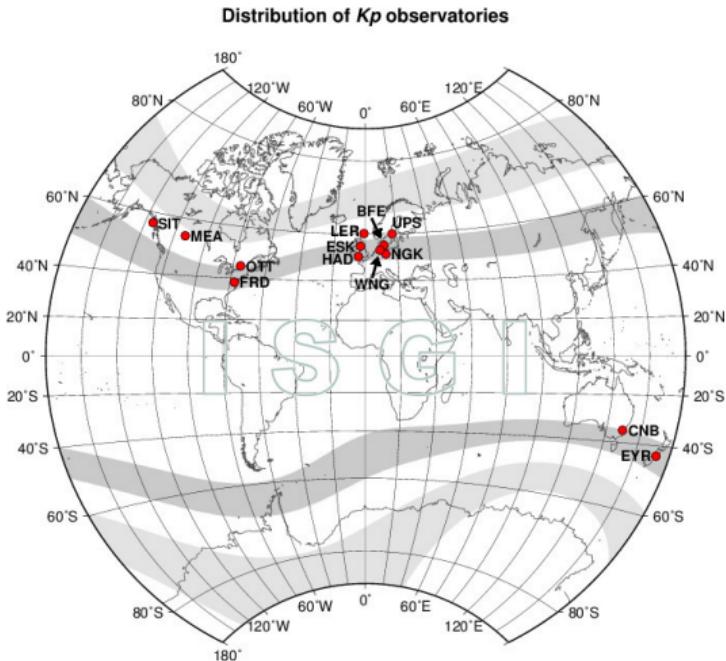
Credit: Hughes (1995, Fig. 9.11)

Factors that influence the reconnection flux rate:

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

Kp index

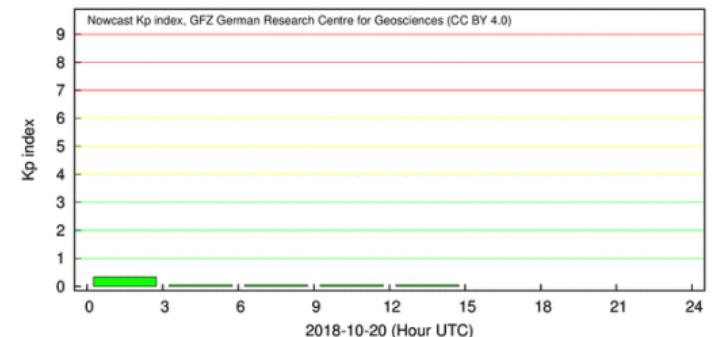
- Planetary geomagnetic disturbance indicator
- 3-hourly variation maxima
- 13 observatories at 50° geomagnetic latitudes
- Scale from 0 to 9



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

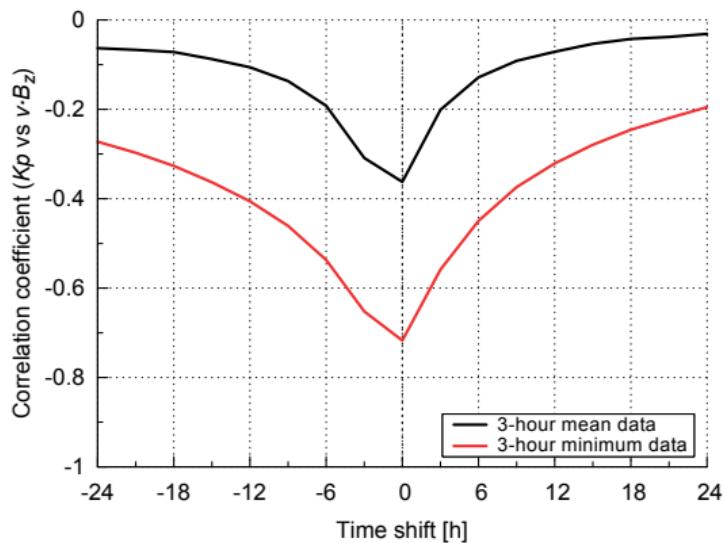
Kp index

Quicklook *Kp*

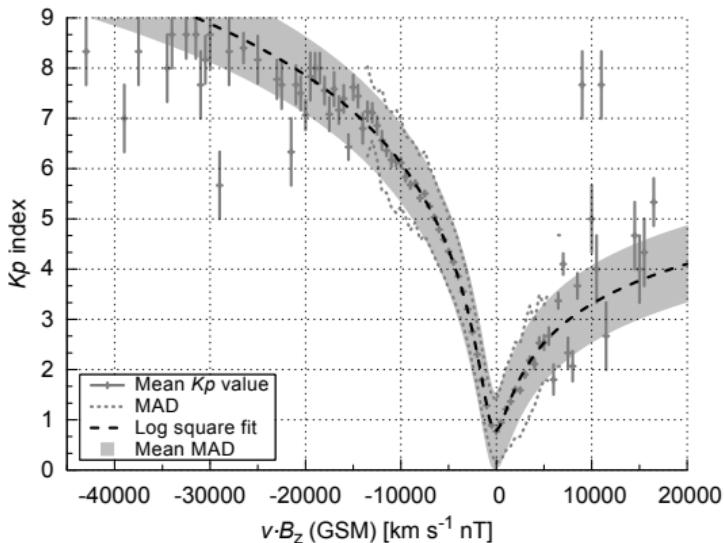
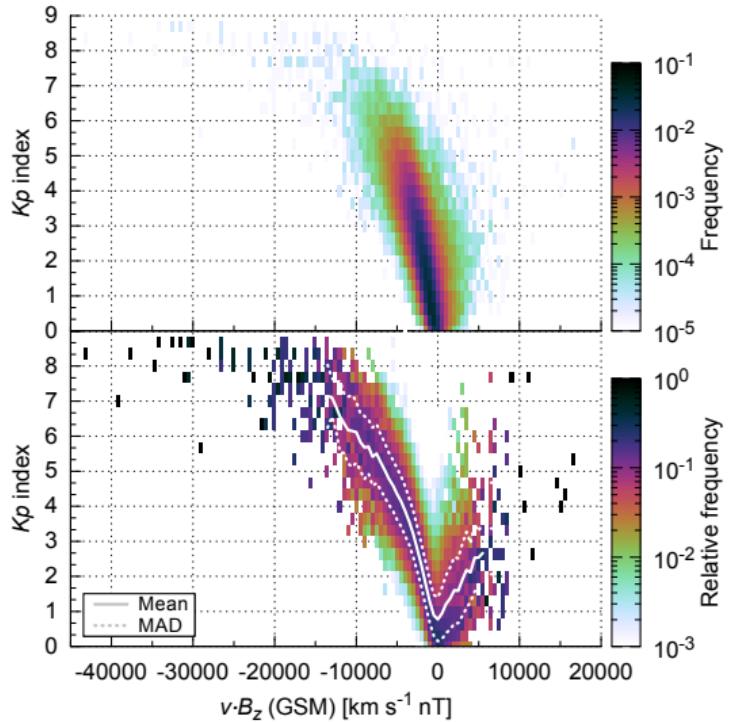


Credit: GFZ Potsdam, 2018

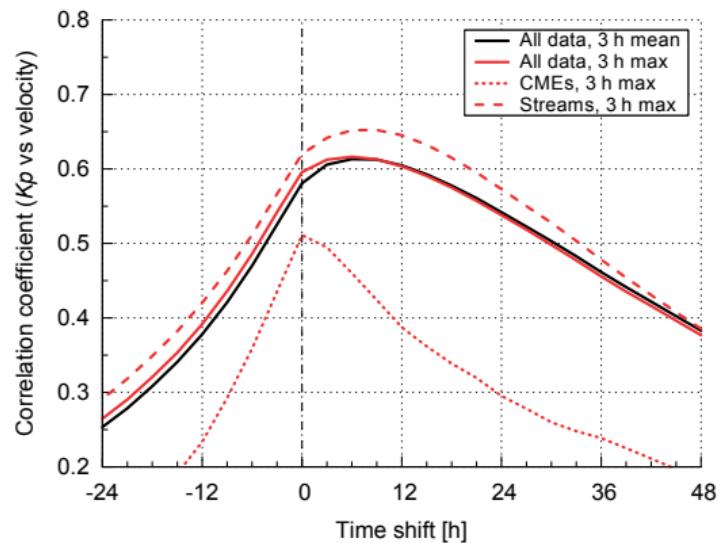
Solar wind electric field



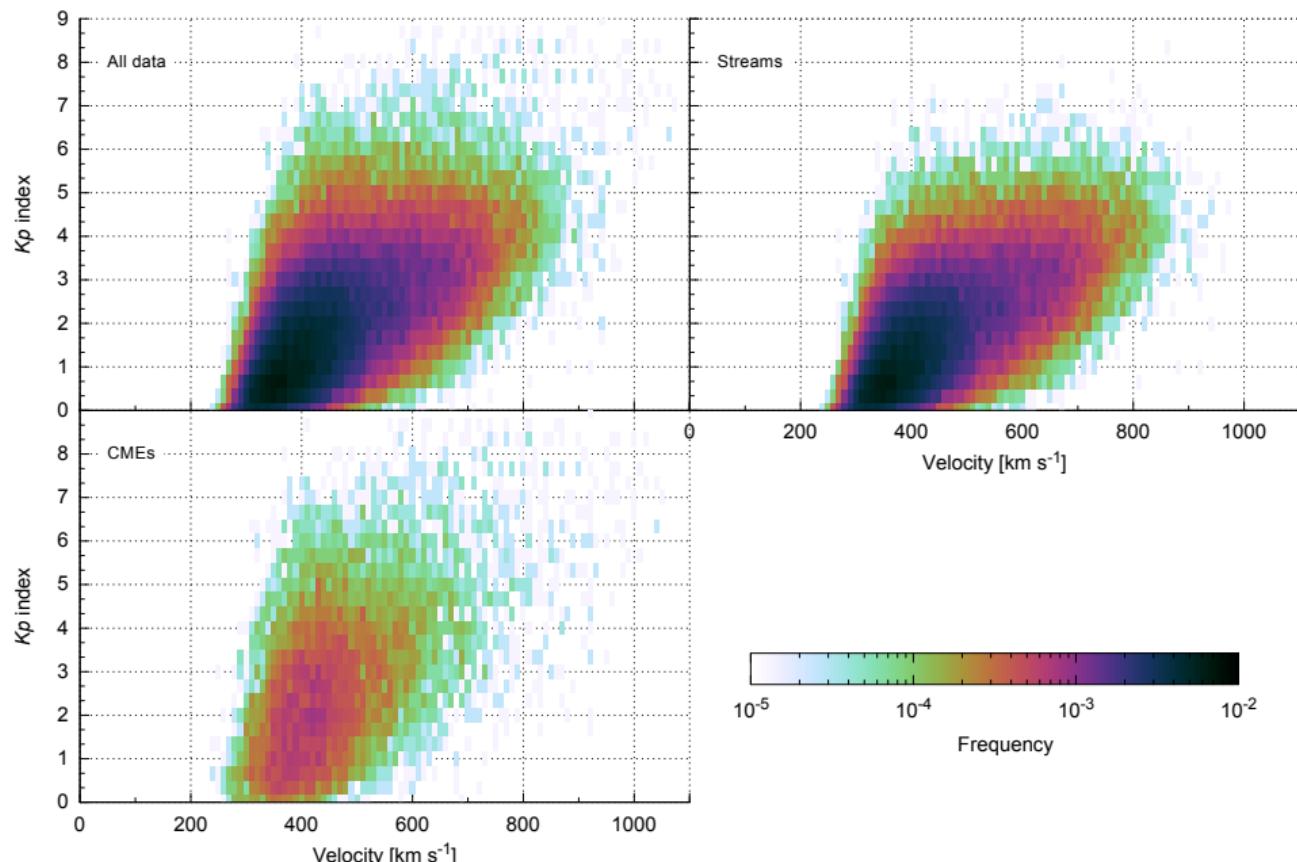
Solar wind electric field

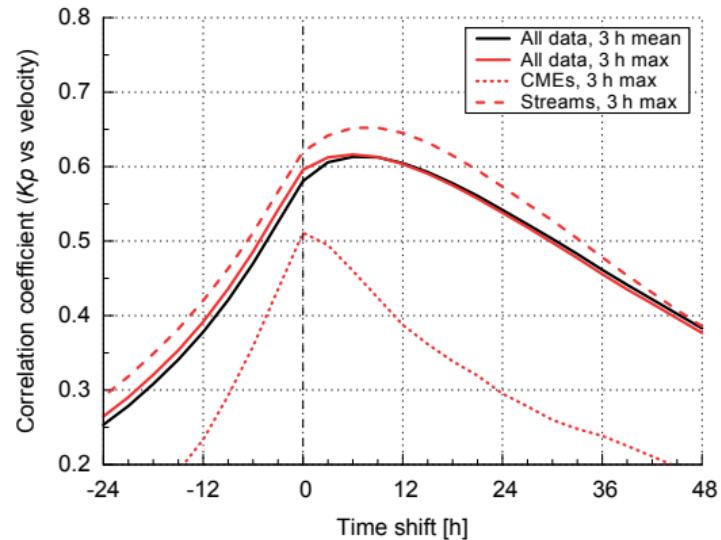


Solar wind velocity

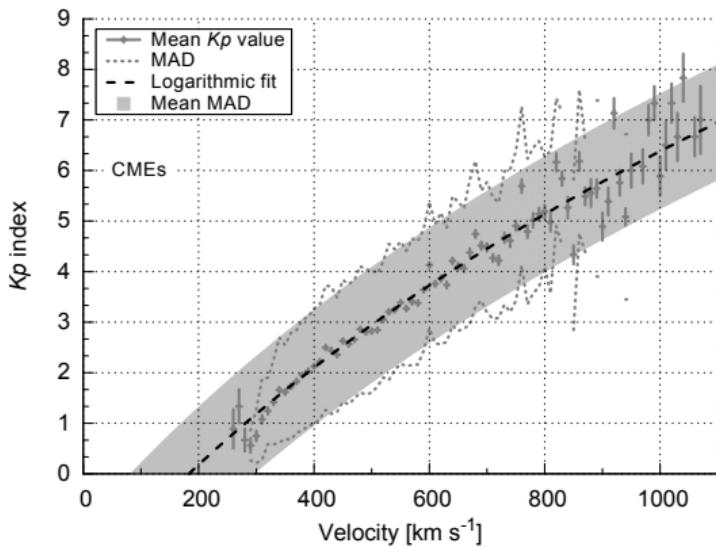
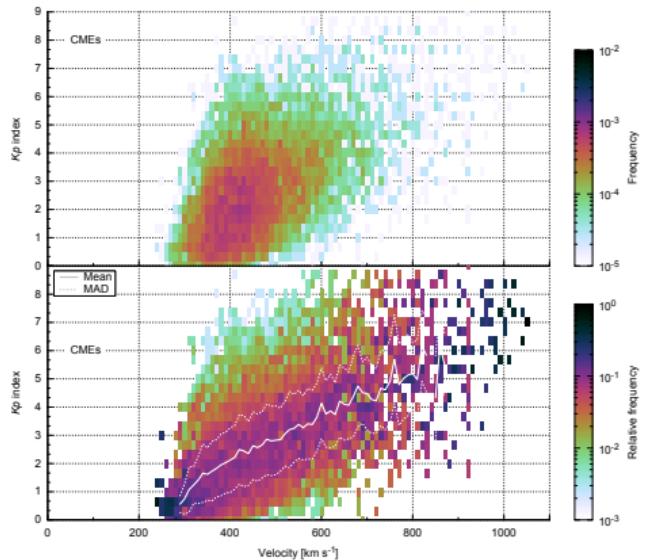


Solar wind velocity

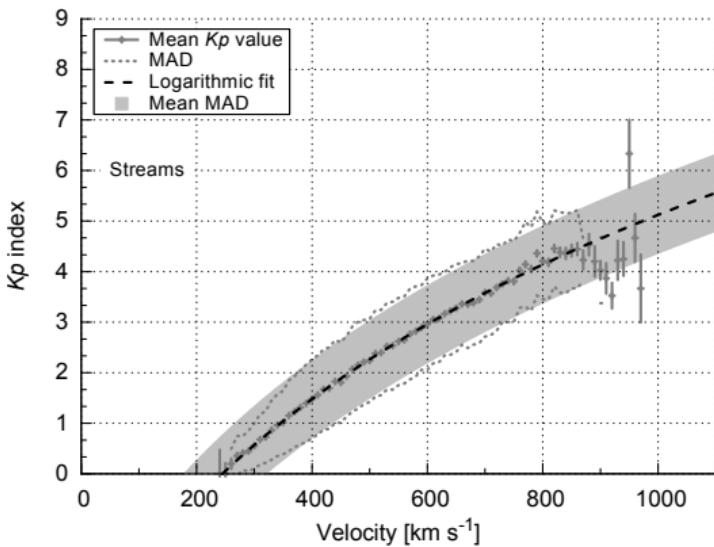
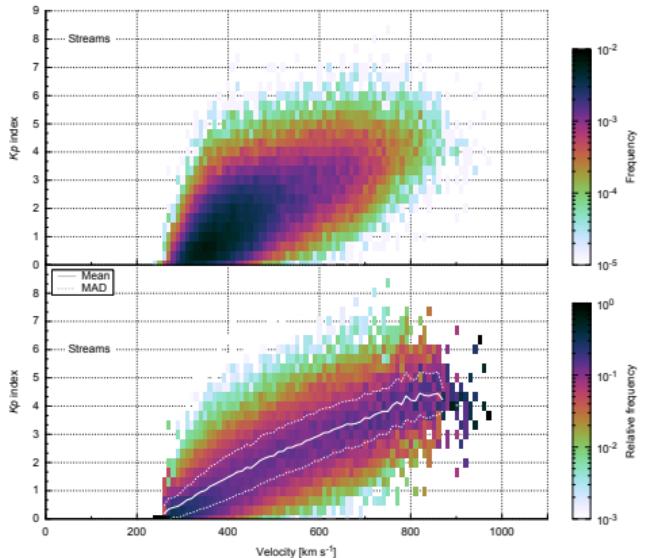


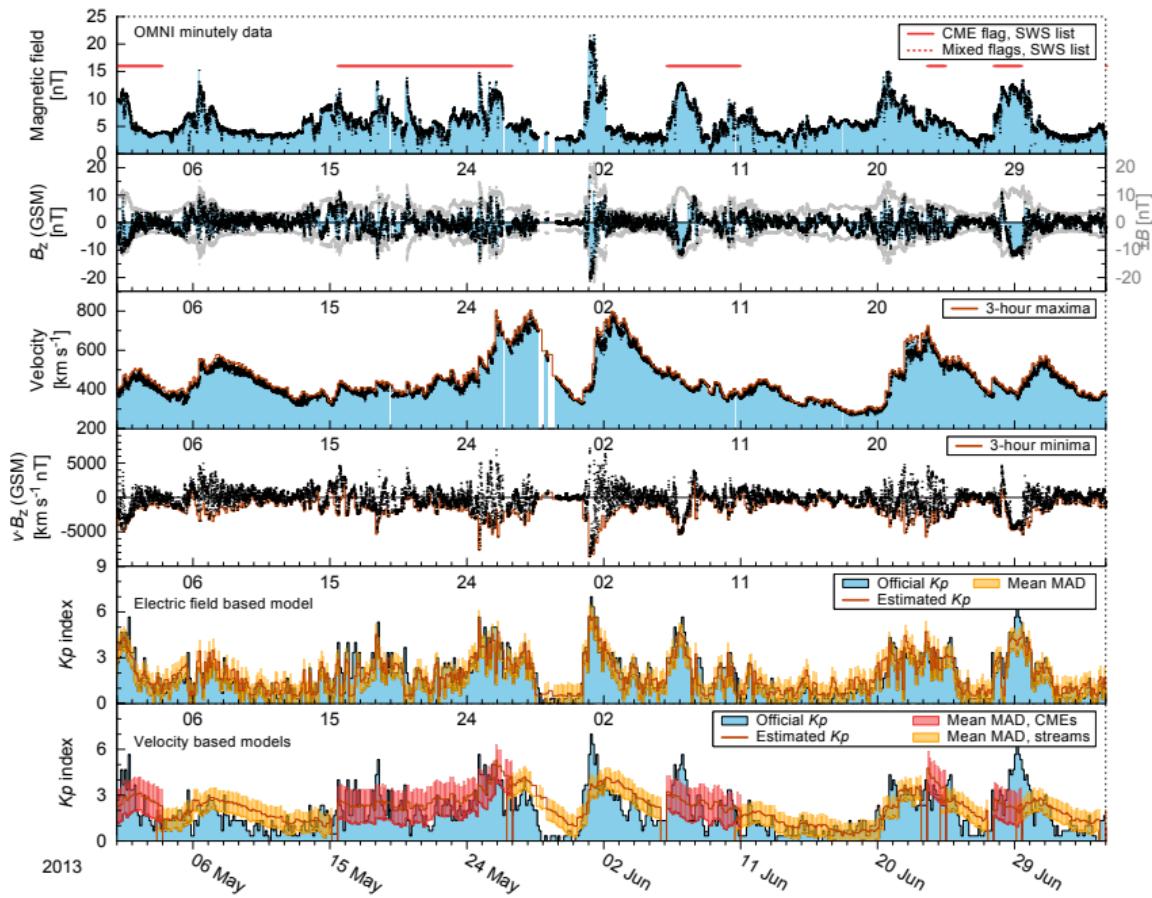


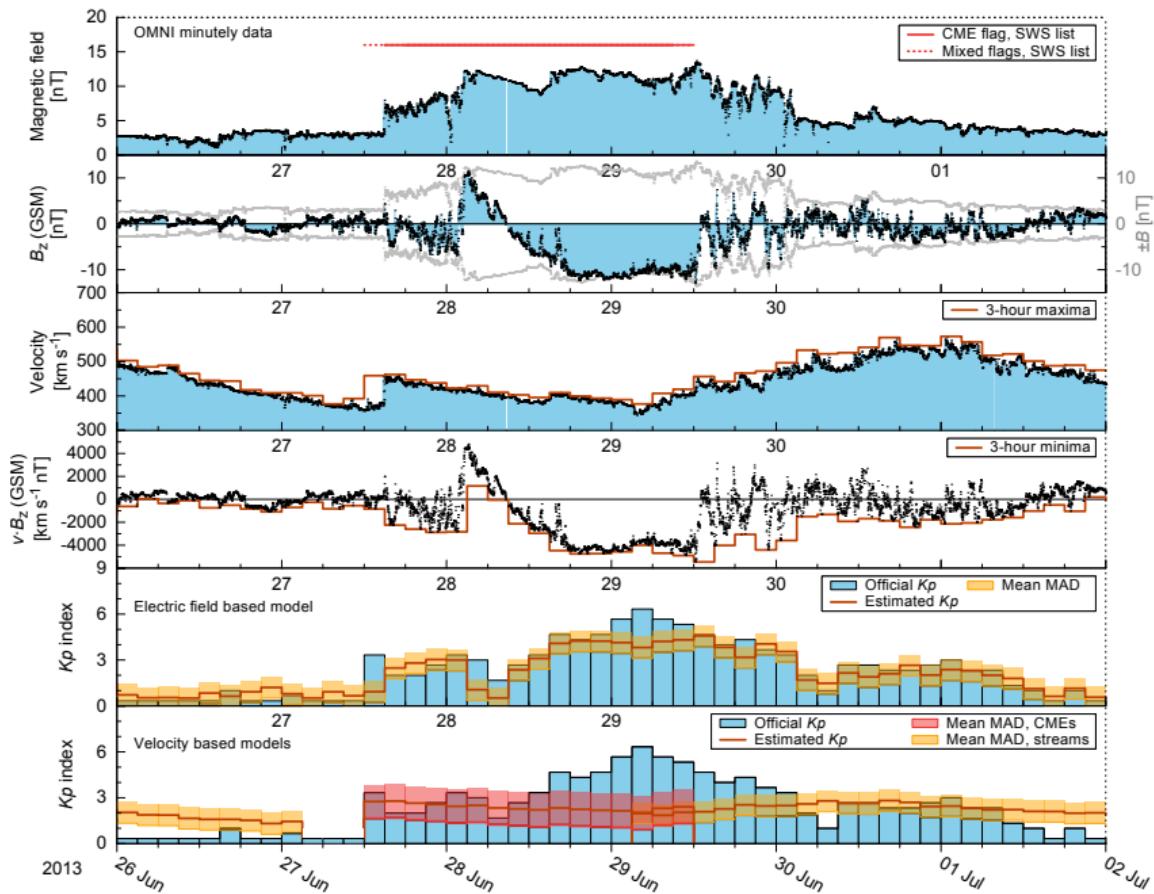
CME velocity



Stream velocity







Results

Predictive K_p models based on relations with

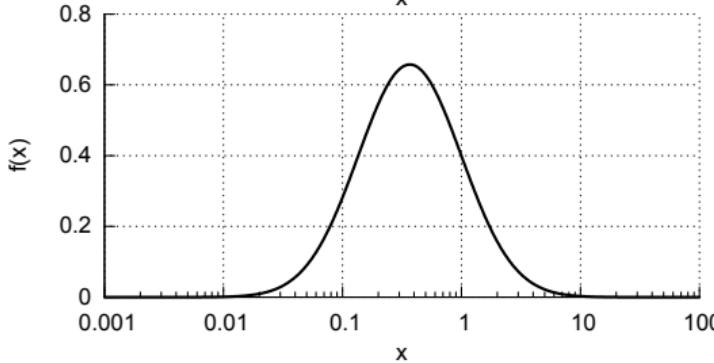
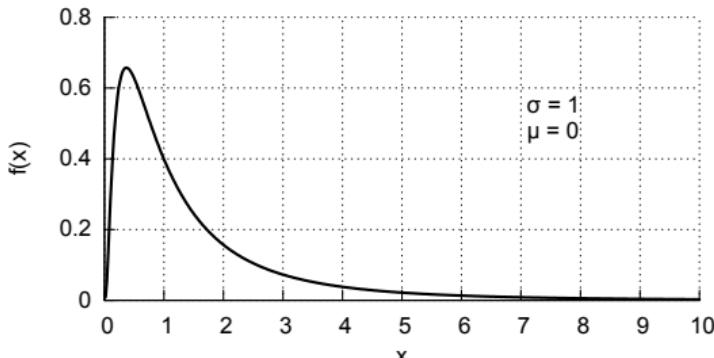
- Solar wind electric field proxy (vB_z)
- Velocity of CME-associated flows (v_{CME})
- Velocity of solar wind streams (v_{stream})

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 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 (μ) and shape parameter (σ).

Median and average:

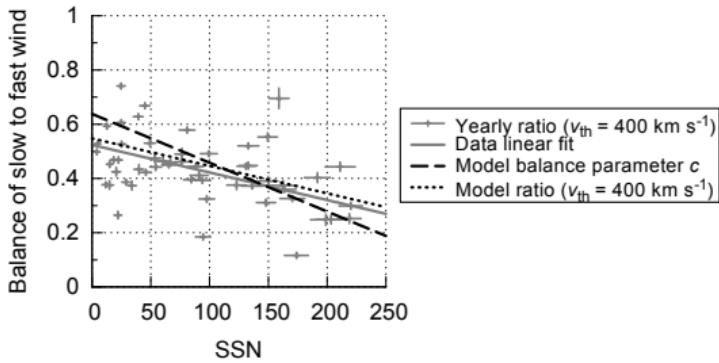
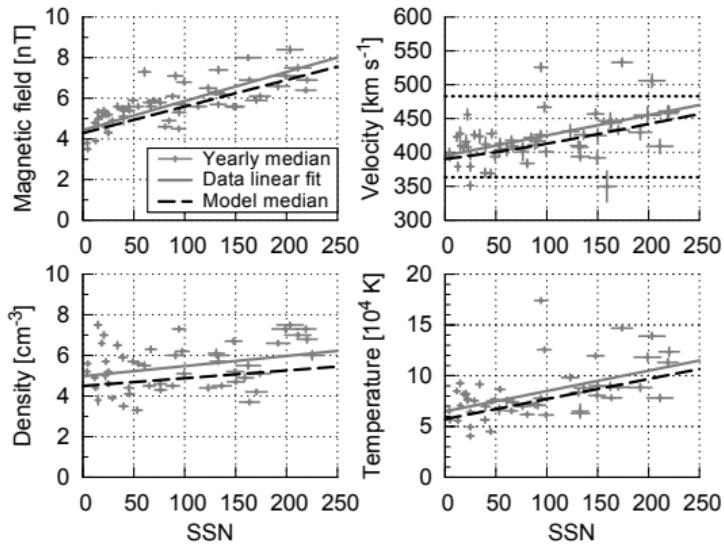
$$x_{\text{med}} = \exp(\mu), \quad x_{\text{avg}} = \exp\left(\mu + \frac{\sigma^2}{2}\right)$$

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

Unsolved problems:

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

Solar activity



PSP perihelia prediction

