

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

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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I use existing solar wind data to derive

- Solar wind model for the inner heliosphere
- Extrapolation to the near-Sun region
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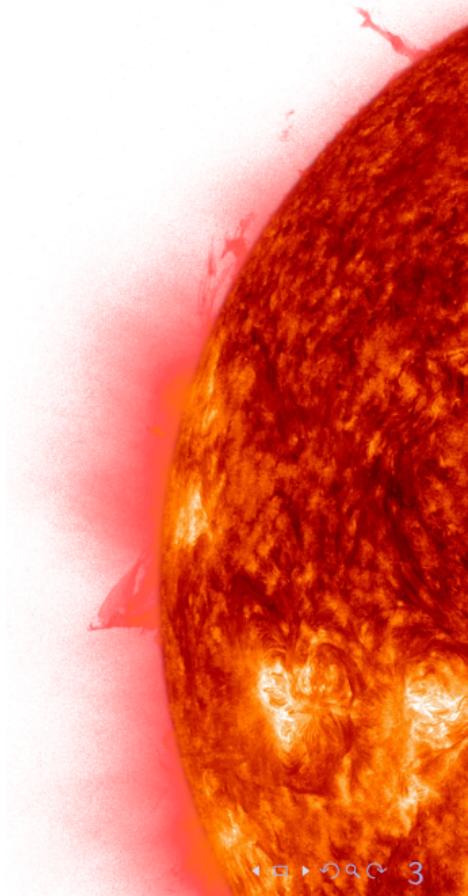
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Empirical solar wind model

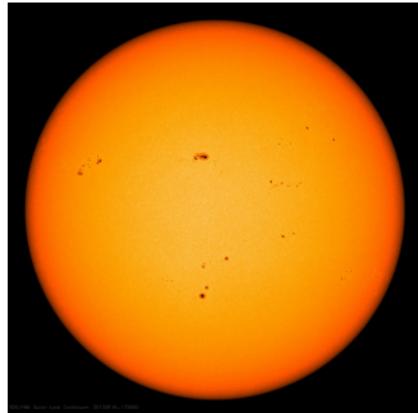
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- Introduction
 - Solar activity
 - Solar wind
 - Parker Solar Probe (PSP)
- Empirical solar wind model
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- Summary

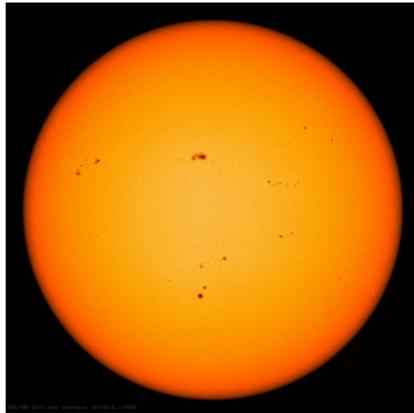


Solar activity

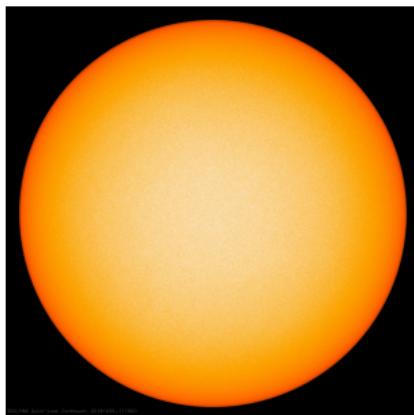


Credit: NASA SDO/HMI, 16 May 2013

Solar activity

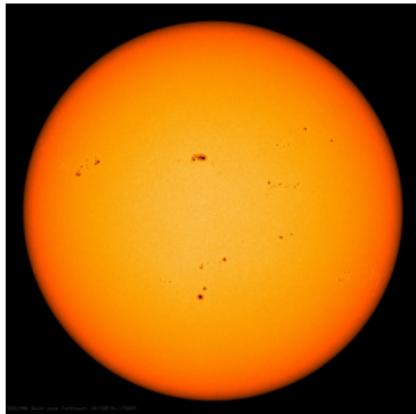


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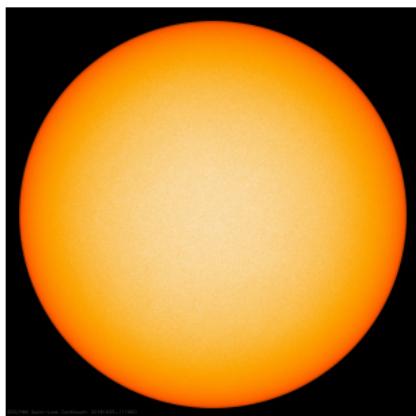


Credit: NASA SDO/HMI, 26 October 2018

Solar activity

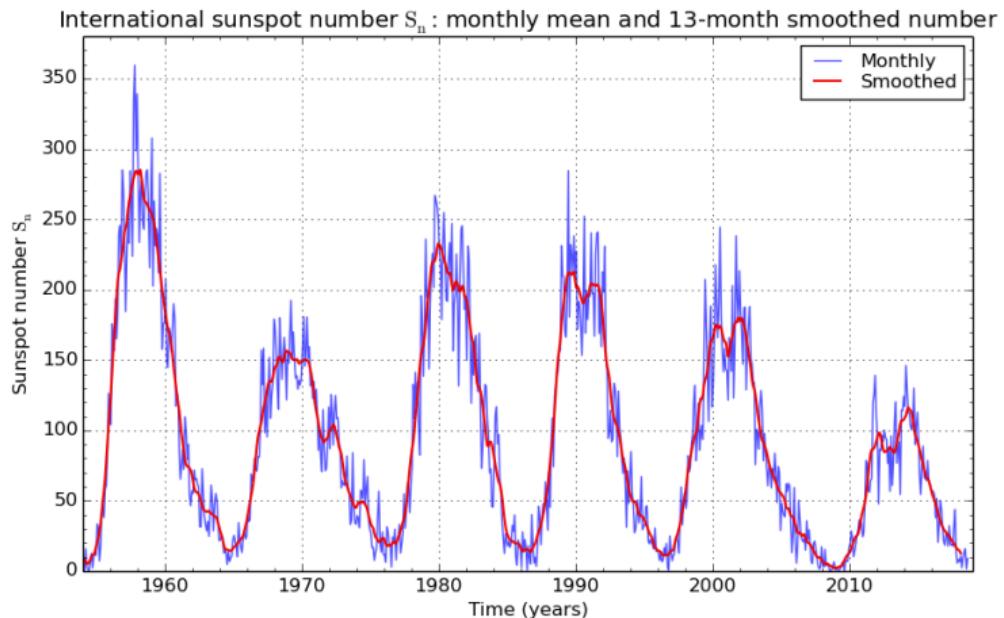


Credit: NASA SDO/HMI, 16 May 2013



Credit: NASA SDO/HMI, 26 October 2018

In 1843 the 11-year periodicity was discovered



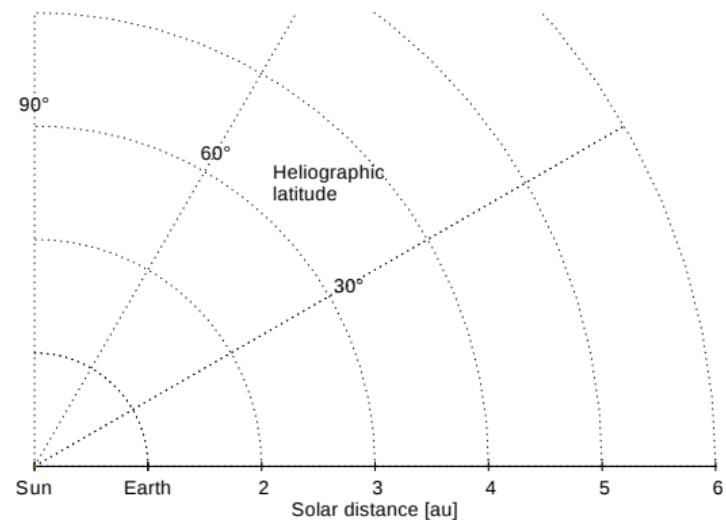
SILSO graphics (<http://sidc.be/silso>) Royal Observatory of Belgium 2018 September 1

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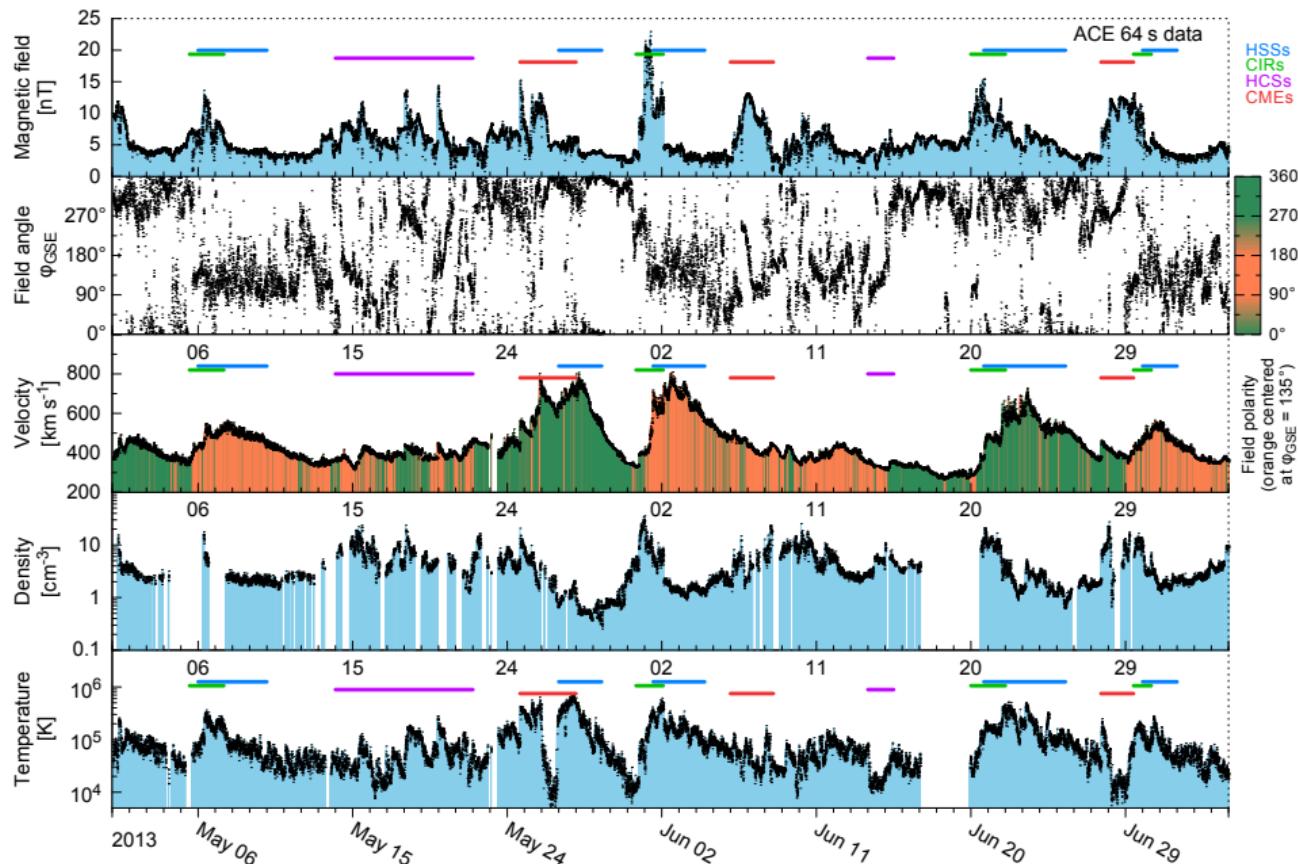
Solar wind

Solar wind

- Theoretical model (Parker, 1958):
Expanding isothermal solar atmosphere
- In-situ measurements confirmed existence in 1959
- Monitored continuously near Earth since 1963
- Composition



Solar wind



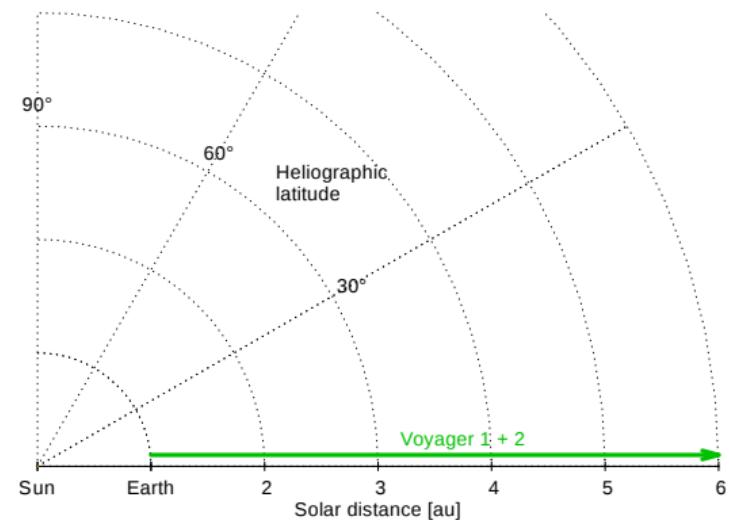
Solar wind

Measured in-situ throughout the
heliosphere:

Solar wind

Measured in-situ throughout the heliosphere:

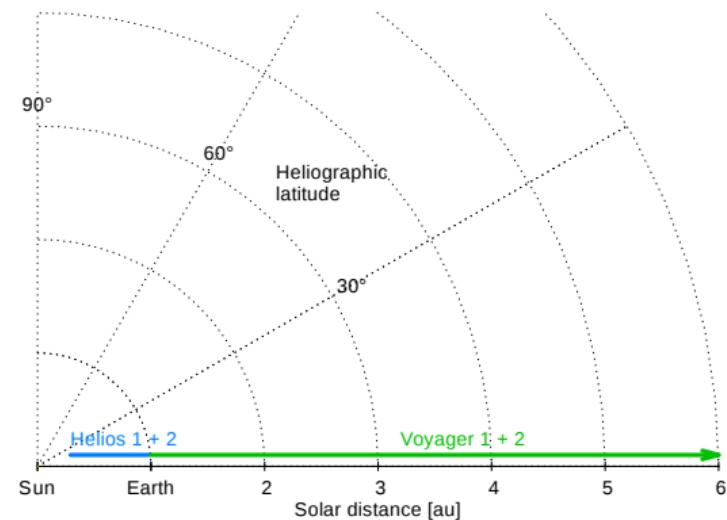
- Voyager 1 & 2 – out to heliopause (1–120 au)



Solar wind

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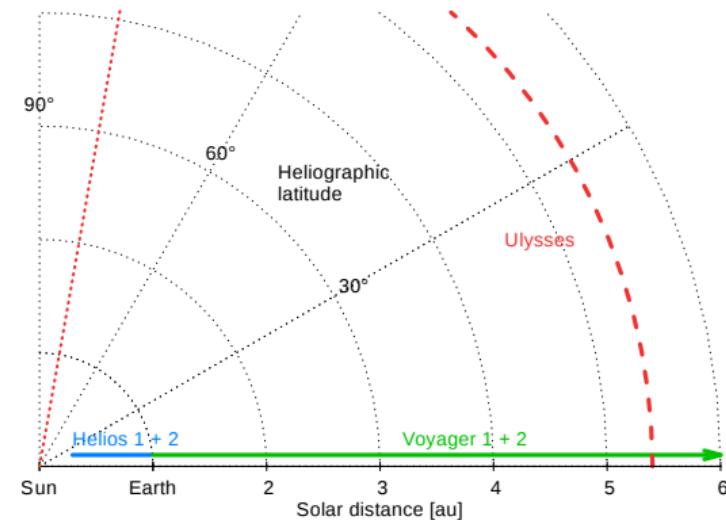
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Solar wind

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
- Solar wind acceleration

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

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

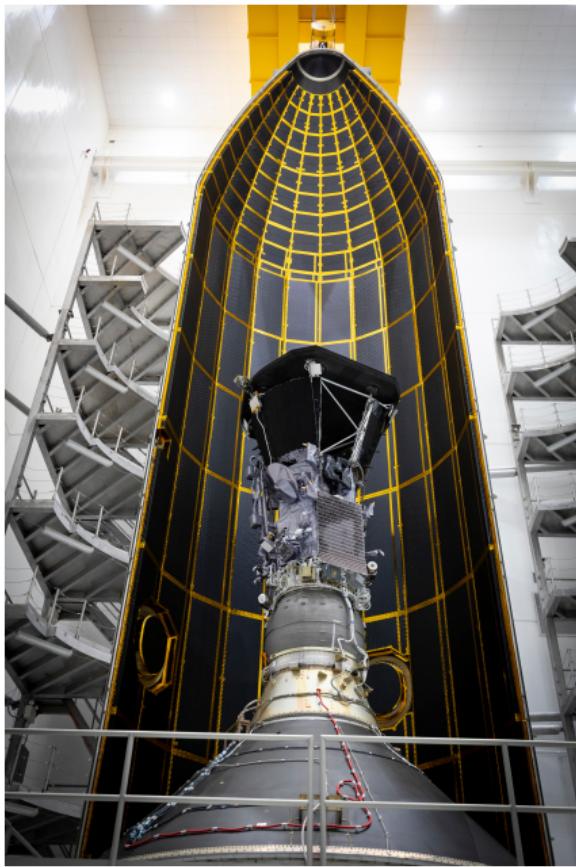
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Scientific instruments

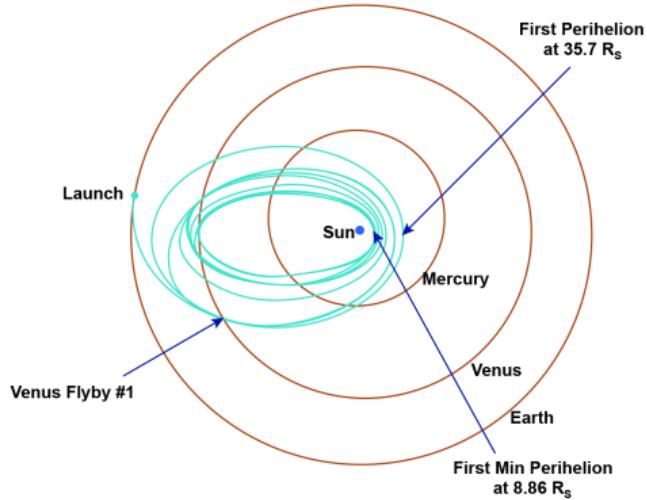
- FIELDS – Electromagnetic Fields Investigation
- IS \odot IS – Integrated Science Investigation of the Sun
- SWEAP – Solar Wind Electrons Alphas and Protons Investigation
- WISPR – Wide-Field Imager for Solar Probe

Parker Solar Probe



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

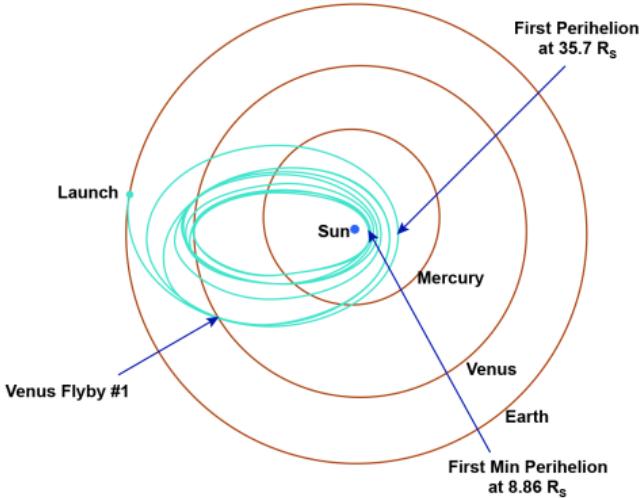
Parker Solar Probe



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

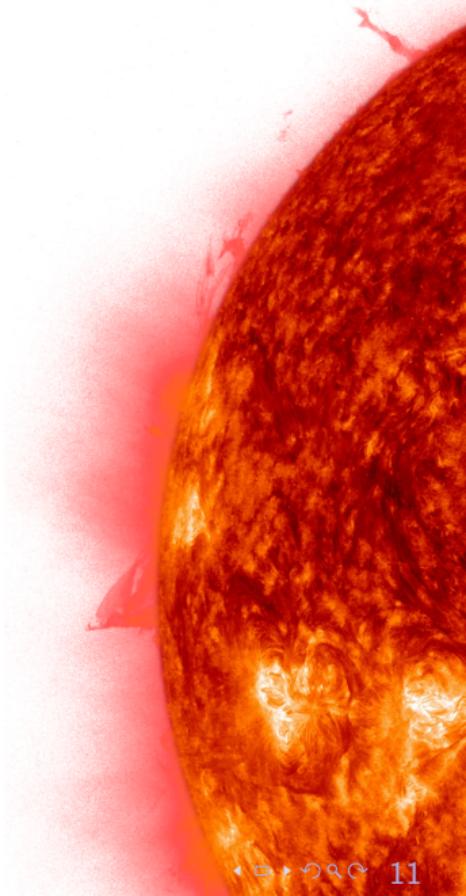
6 November

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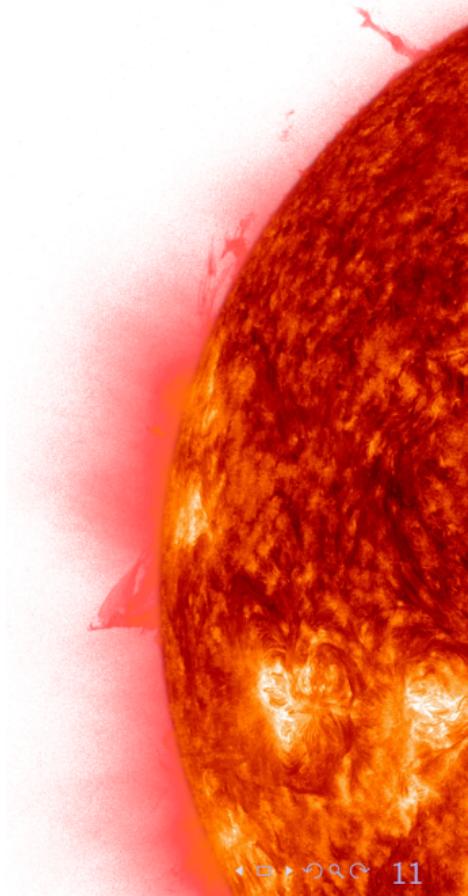
24 December 2024

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

C



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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
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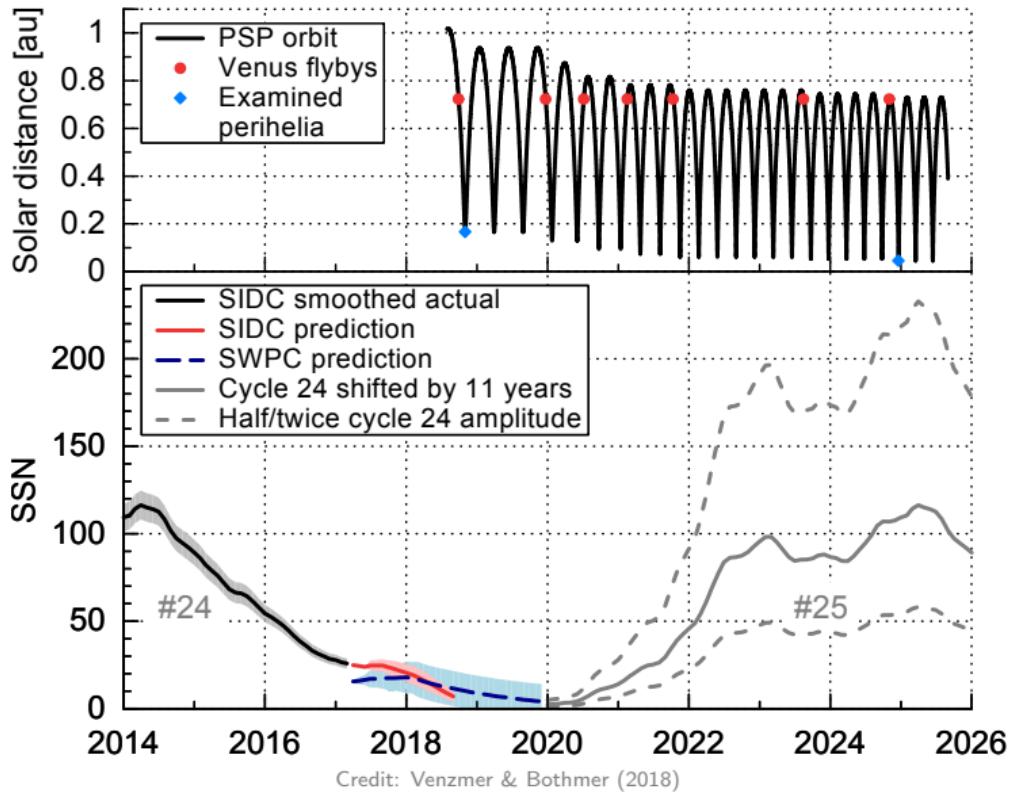
Model concept:

Frequency distributions shifted according to
solar activity and solar distance

Solar wind key parameters

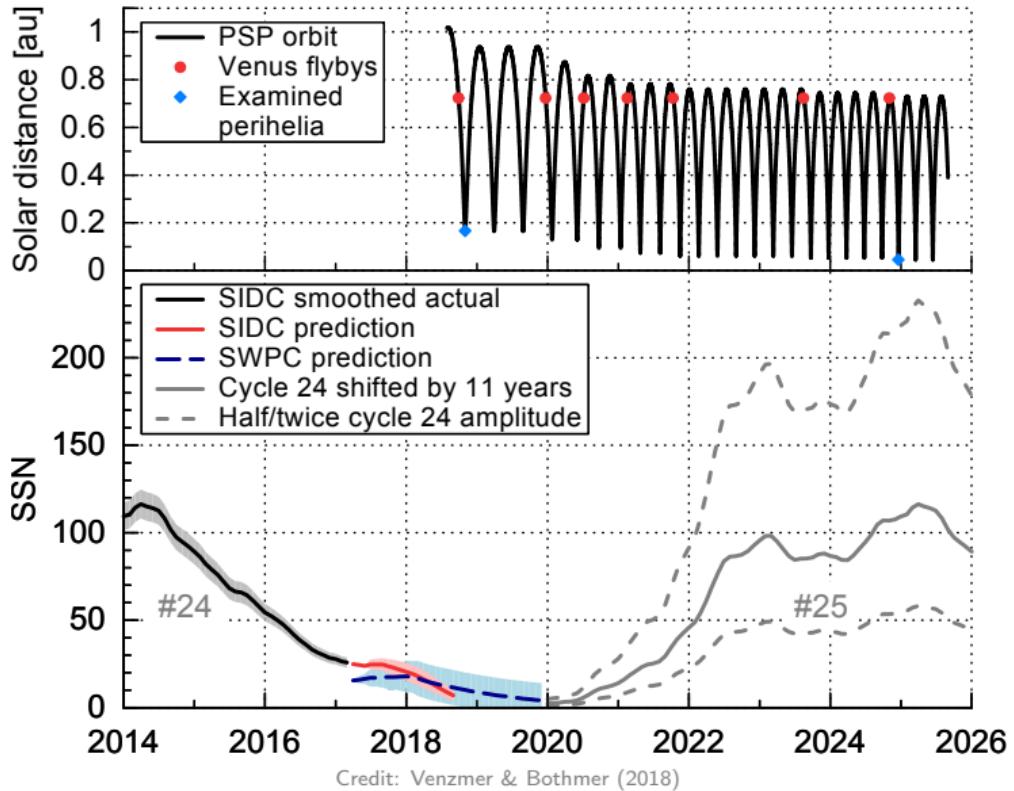
- Magnetic field strength
- Velocity
- Density
- Temperature

PSP distance and solar activity



Credit: Venzmer & Bothmer (2018)

PSP distance and solar activity



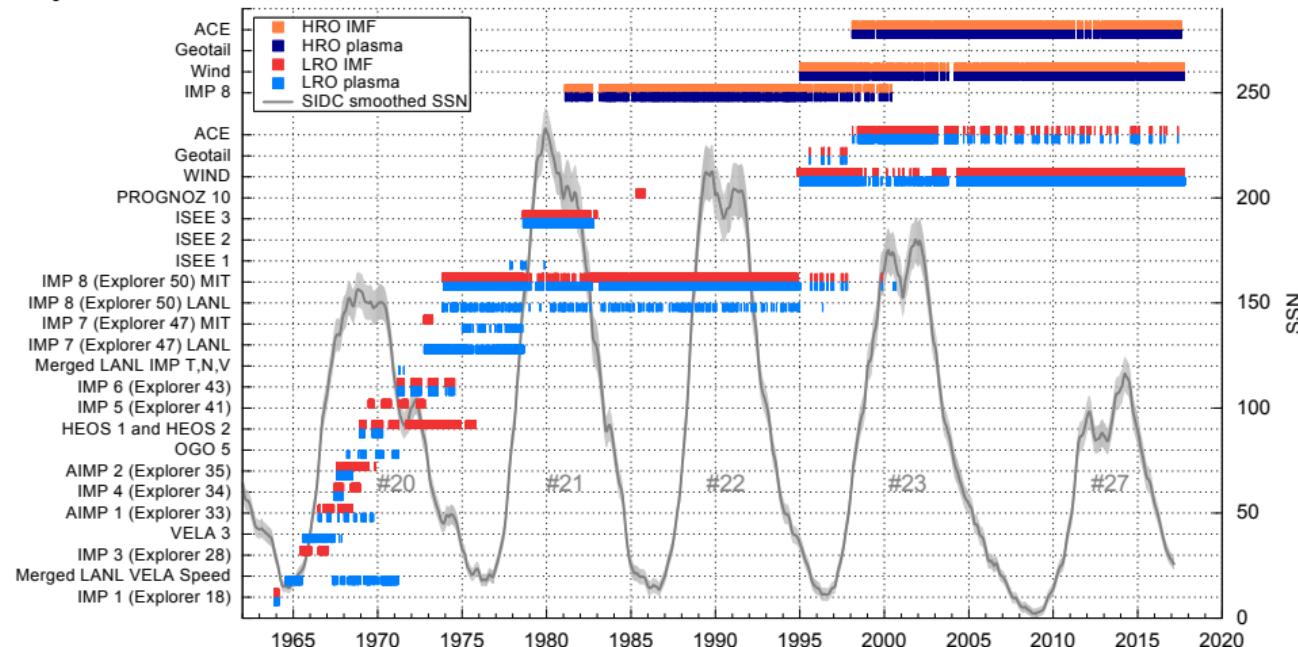
Perihelion #1
2018: solar minimum

Perihelion #22
2024: solar maximum

Solar wind data

OMNI data set (King & Papitashvili, 2005)

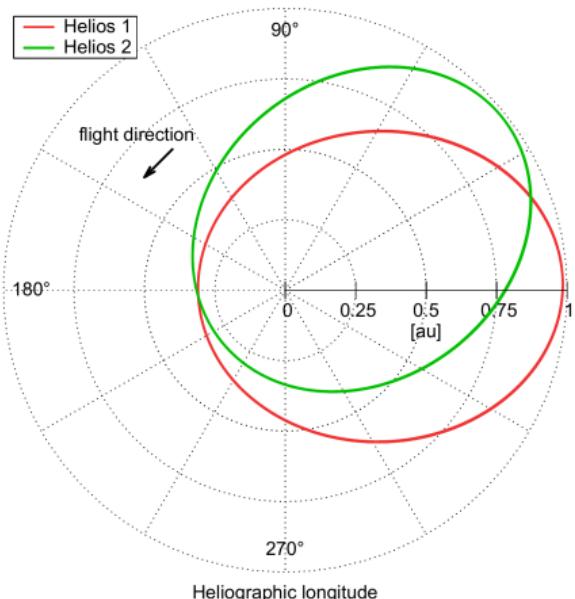
- intercalibrated multi-spacecraft data
- time-shifted to the bow shock of the magnetosphere
- hourly data since 1963



Solar wind data

Helios data set (Rosenbauer et al., 1977)

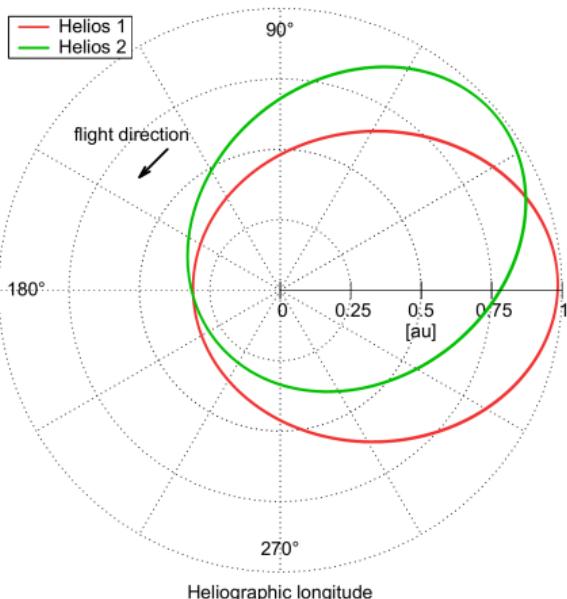
- Helios 1 and Helios 2 probes
- solar distance range 0.29–0.98 au
- hourly data from 1974–1981



Solar wind data

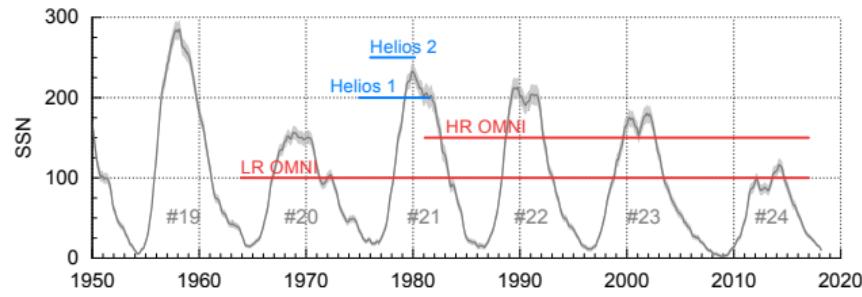
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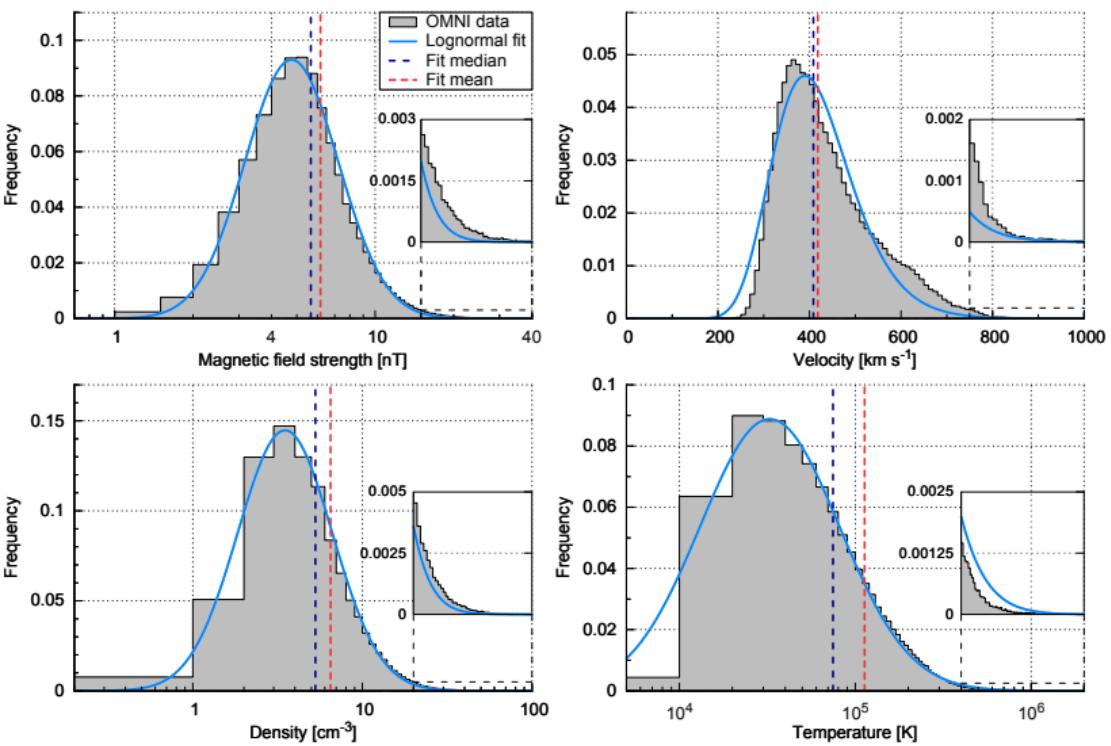
Solar wind model data use

- 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

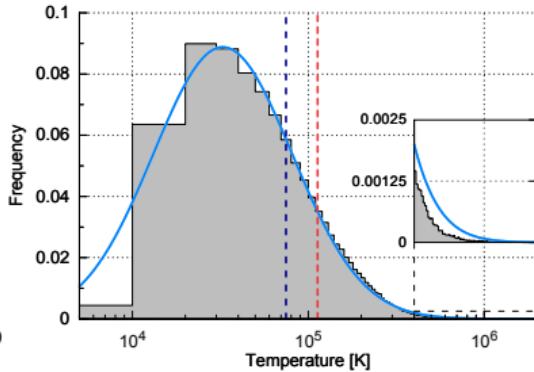
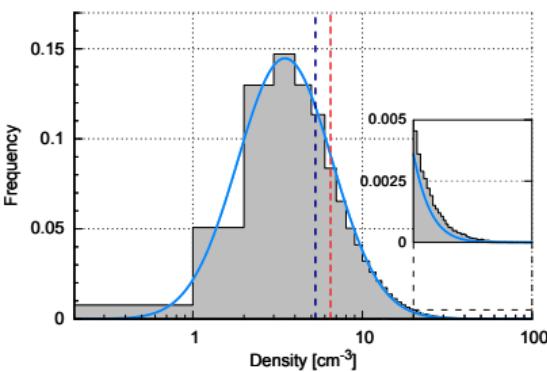
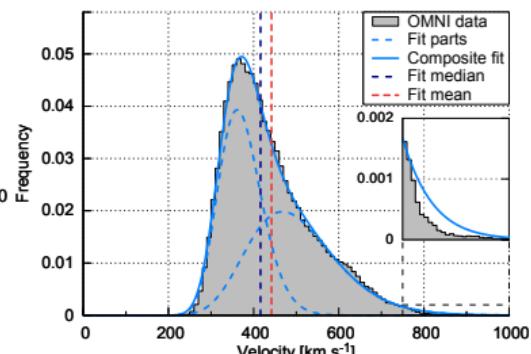
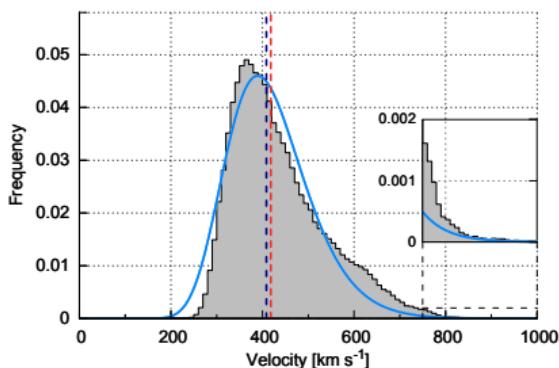
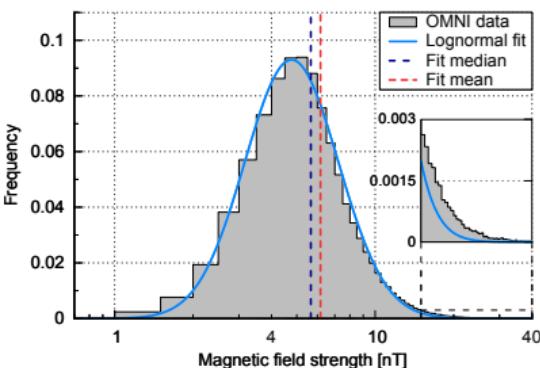
Hourly OMNI data from 1963 to 2016



Credit: Venzmer & Bothmer (2018)

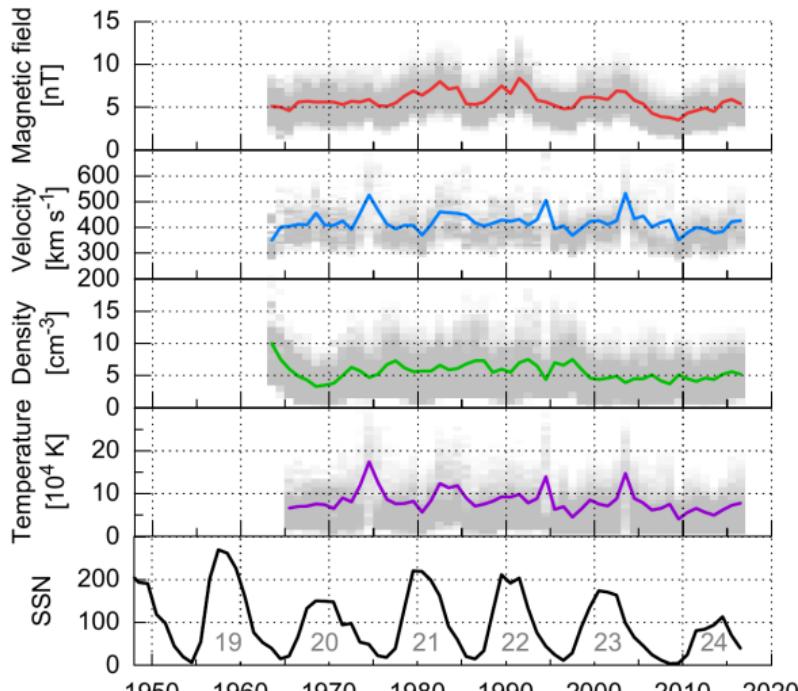
Frequency distributions

Hourly OMNI data from 1963 to 2016



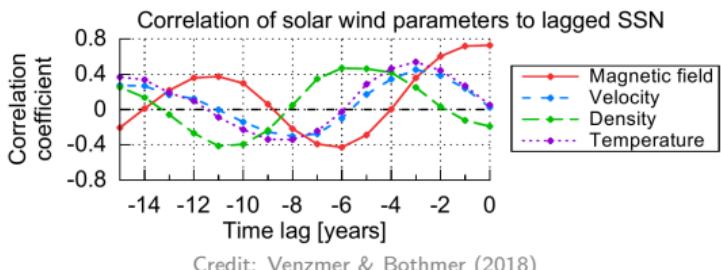
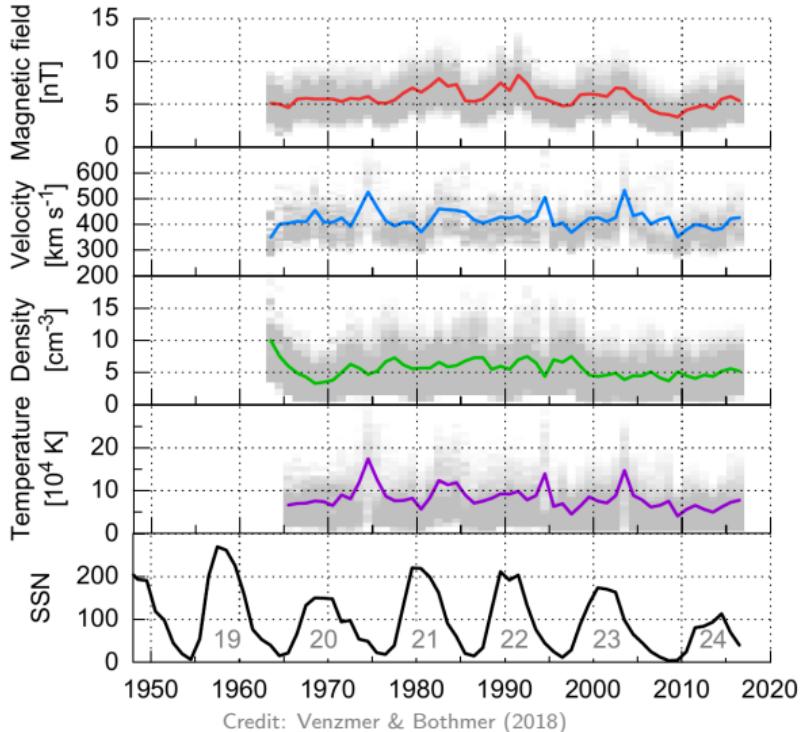
Credit: Venzmer & Bothmer (2018)

Solar activity dependence



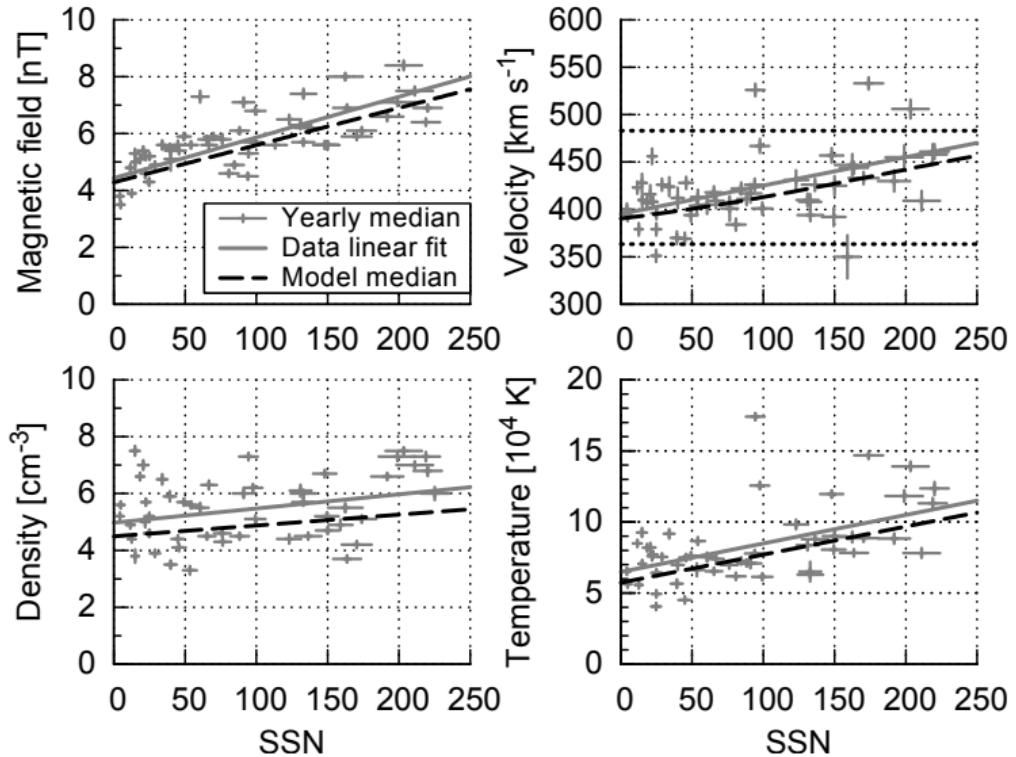
Credit: Venzmer & Bothmer (2018)

Solar activity dependence



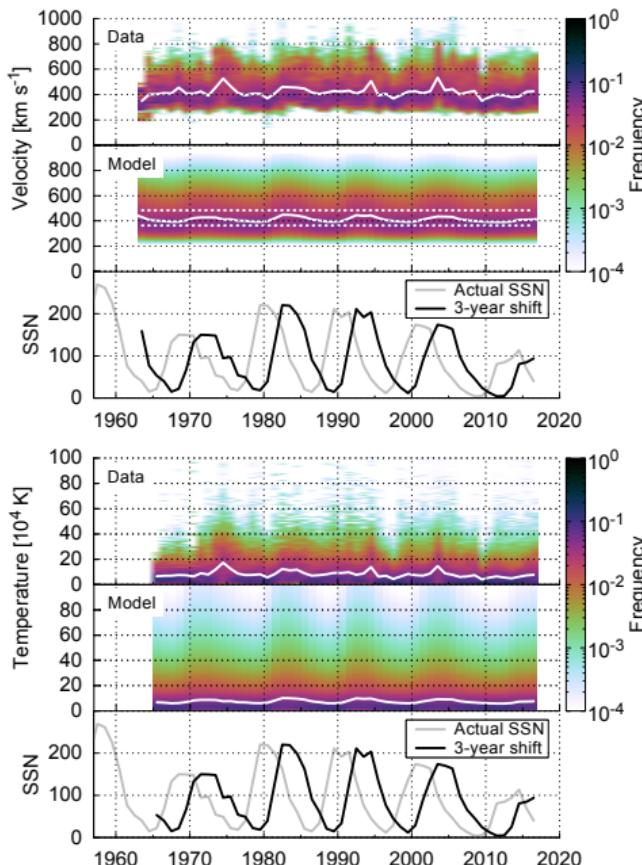
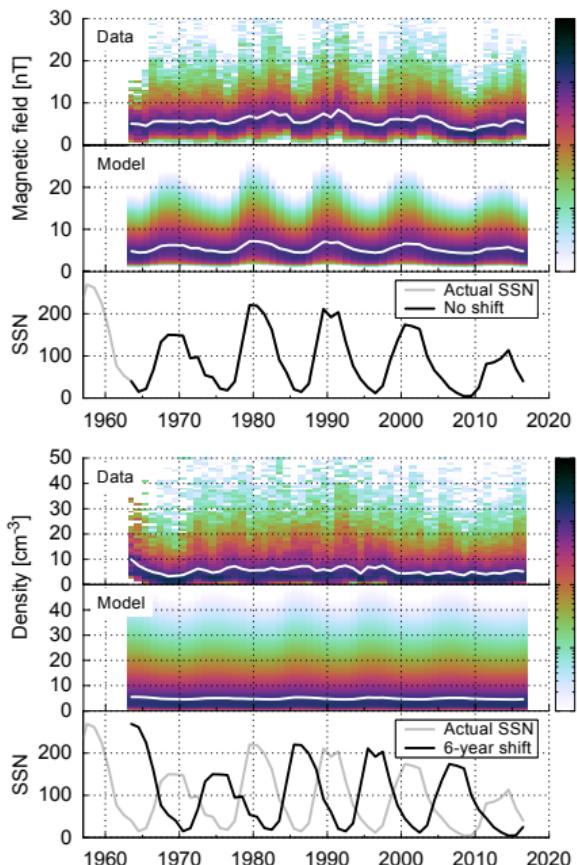
Credit: Venzmer & Bothmer (2018)

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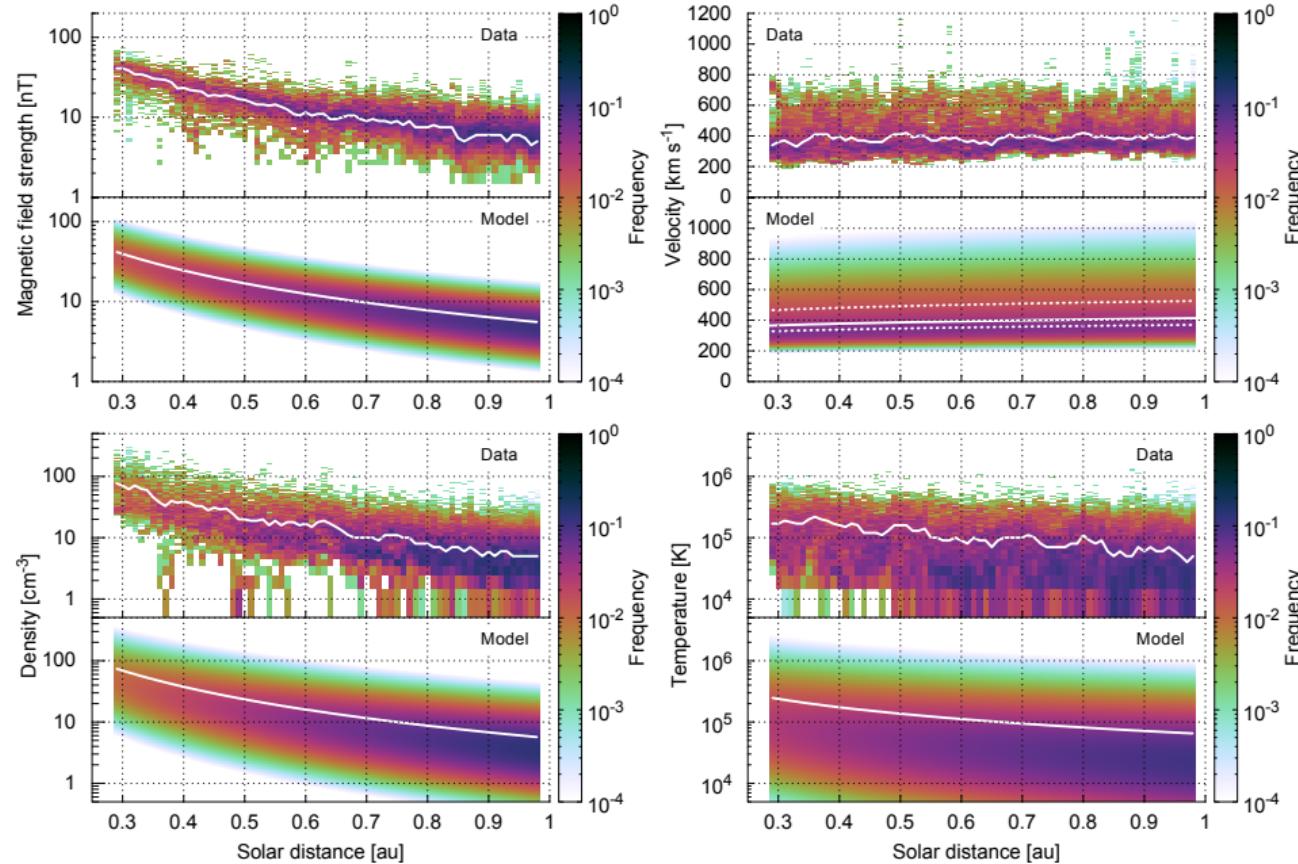
Credit: Venzmer & Bothmer (2018)

Solar activity dependence



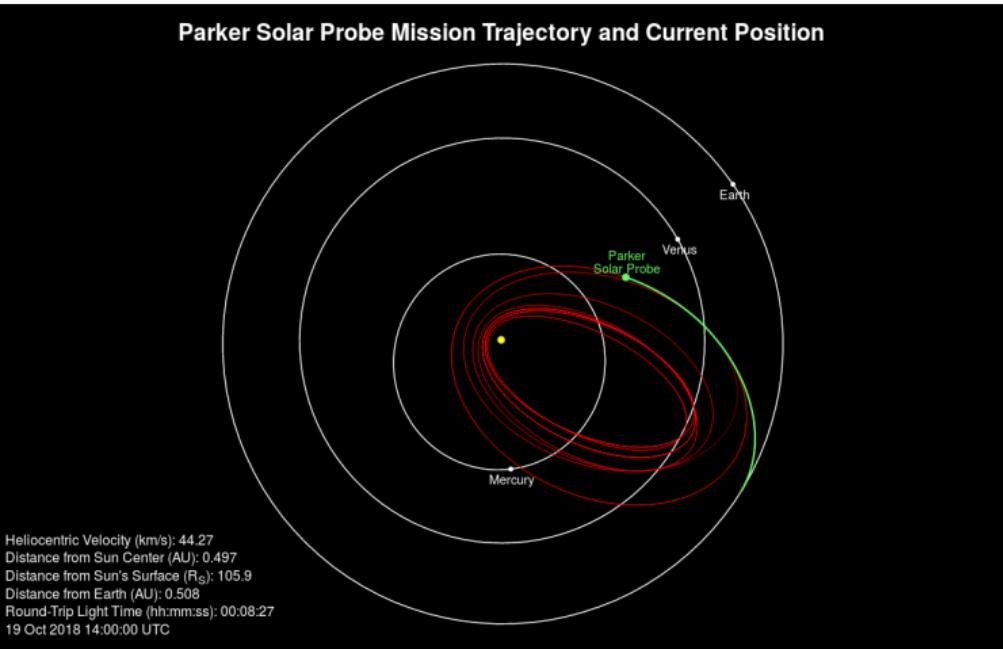
Credit: Venzmer & Bothmer (2018)

Solar distance dependence – Helios data



Credit: Venzmer & Bothmer (2018)

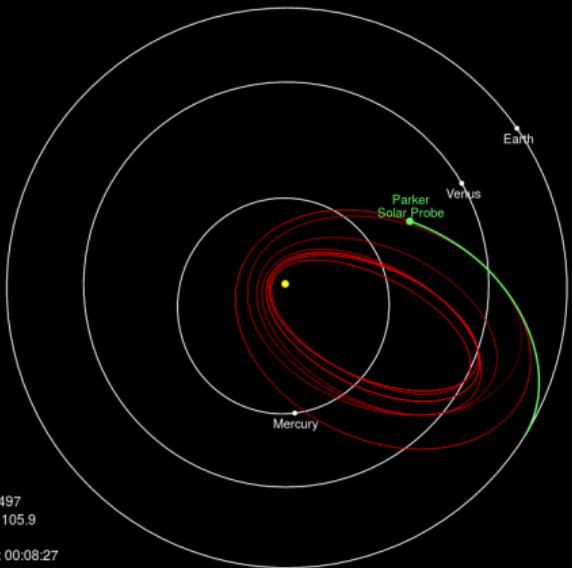
Prediction for PSP orbit



Credit: NASA

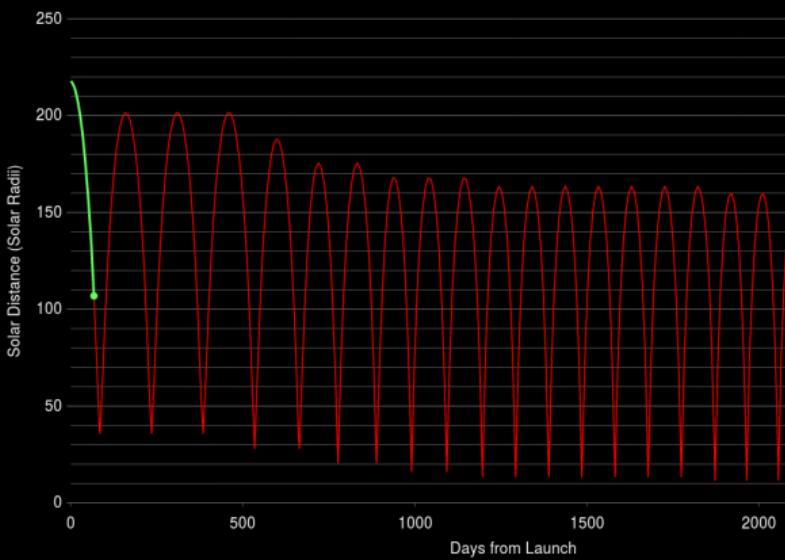
Prediction for PSP orbit

Parker Solar Probe Mission Trajectory and Current Position



Credit: NASA

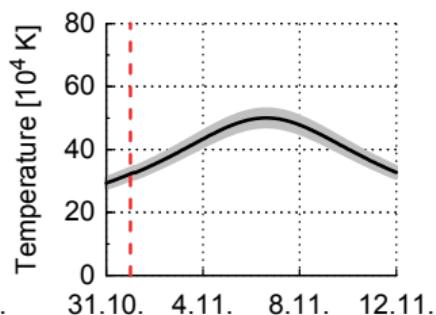
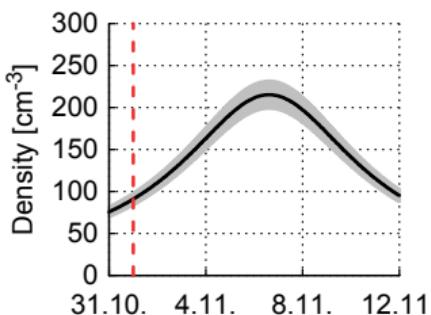
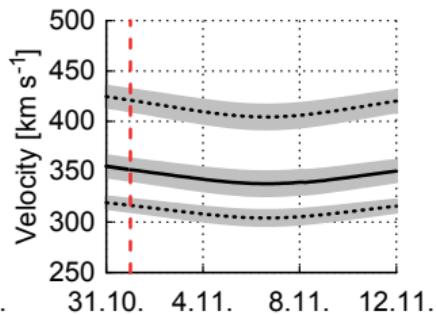
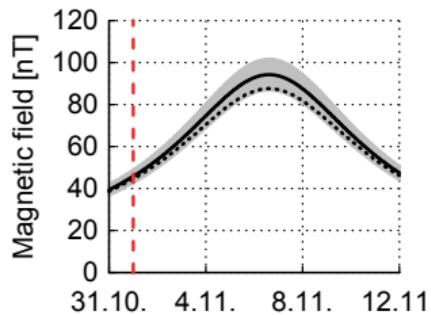
Parker Solar Probe Distance from Sun



Credit: NASA

Prediction for PSP orbit

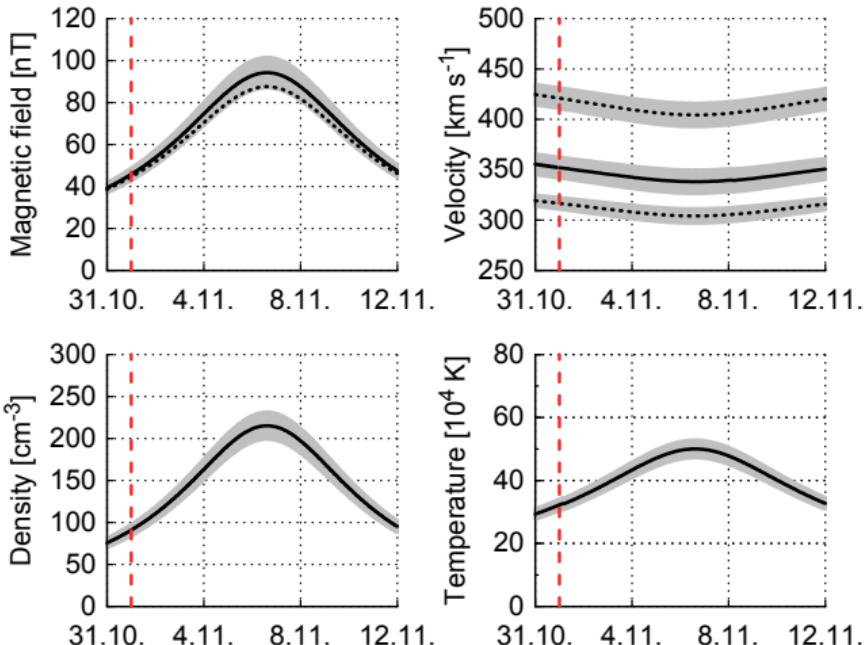
Perihelion #1



November 2018

Prediction for PSP orbit

Perihelion #1



November 2018

Predicted values at $36.7 R_{\odot}$

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

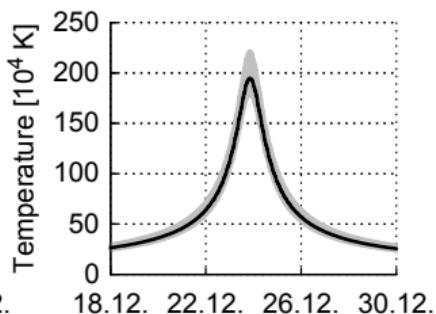
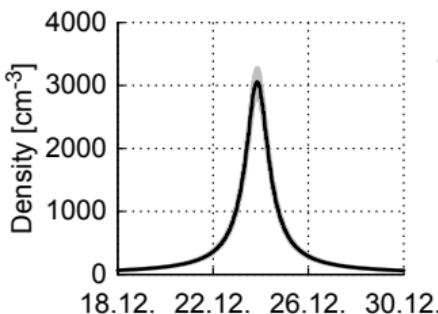
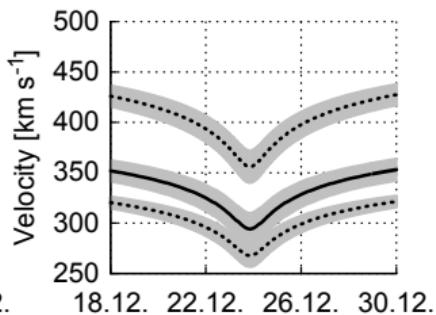
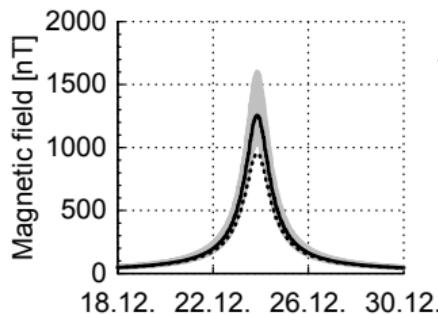
$$v = 340 \text{ km s}^{-1}$$

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

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

Prediction for PSP orbit

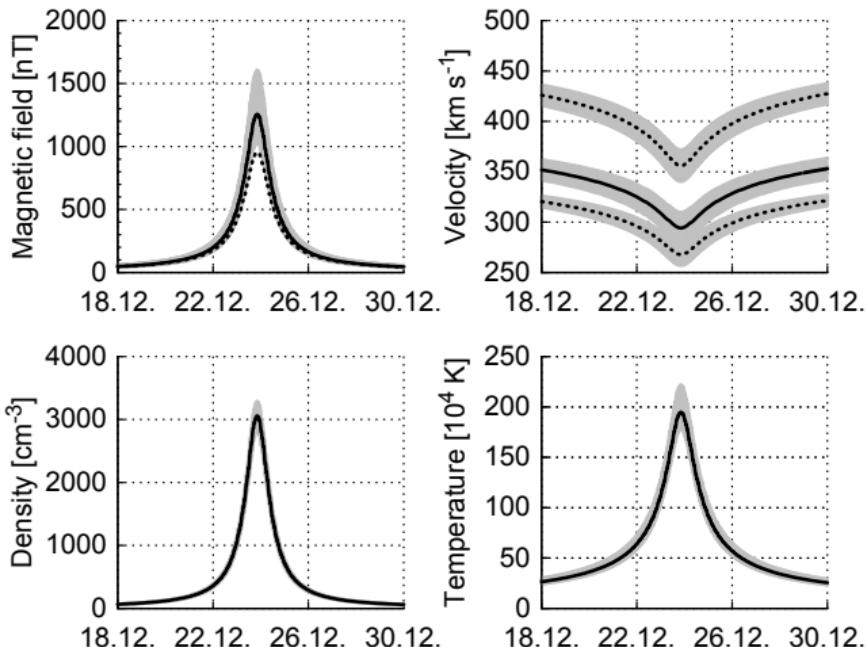
Perihelion #22 (first closest)



December 2024

Prediction for PSP orbit

Perihelion #22 (first closest)



December 2024

Predicted values at $9.86 R_{\odot}$

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

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

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

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

Comparison with other studies

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- Magnetic field values are consistent with theoretical models (Parker, 1958; Banaszkiewicz et al., 1998)
- Studies reveal slow wind velocities of 200 km s^{-1} (Sheeley et al., 1997; Wang et al., 2000)

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- Near-Sun coronal temperatures yield 2–3 MK (Billings, 1959; Liebenberg et al., 1975)

Remote observations show the limits of the extrapolation

Velocity and temperature are overestimated

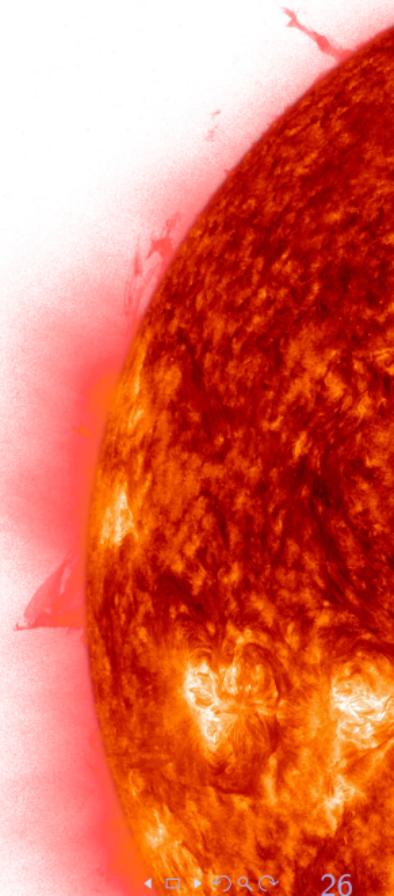
⇒ Solar wind is still being heated and accelerated up to $20 R_{\odot}$

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

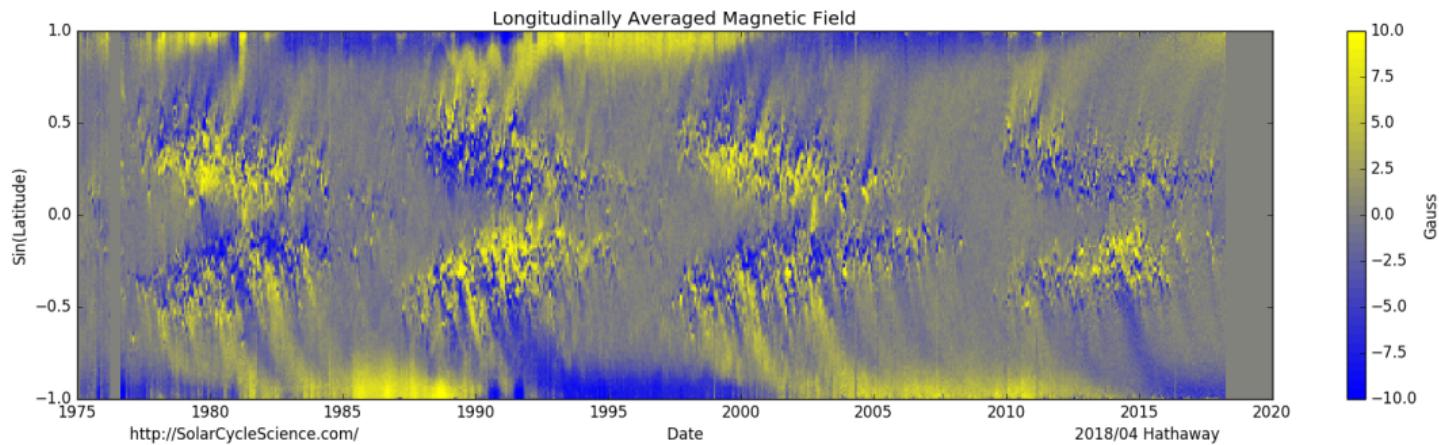
Solar activity

Magnetic butterfly diagram

Geomagnetic impact of the solar wind

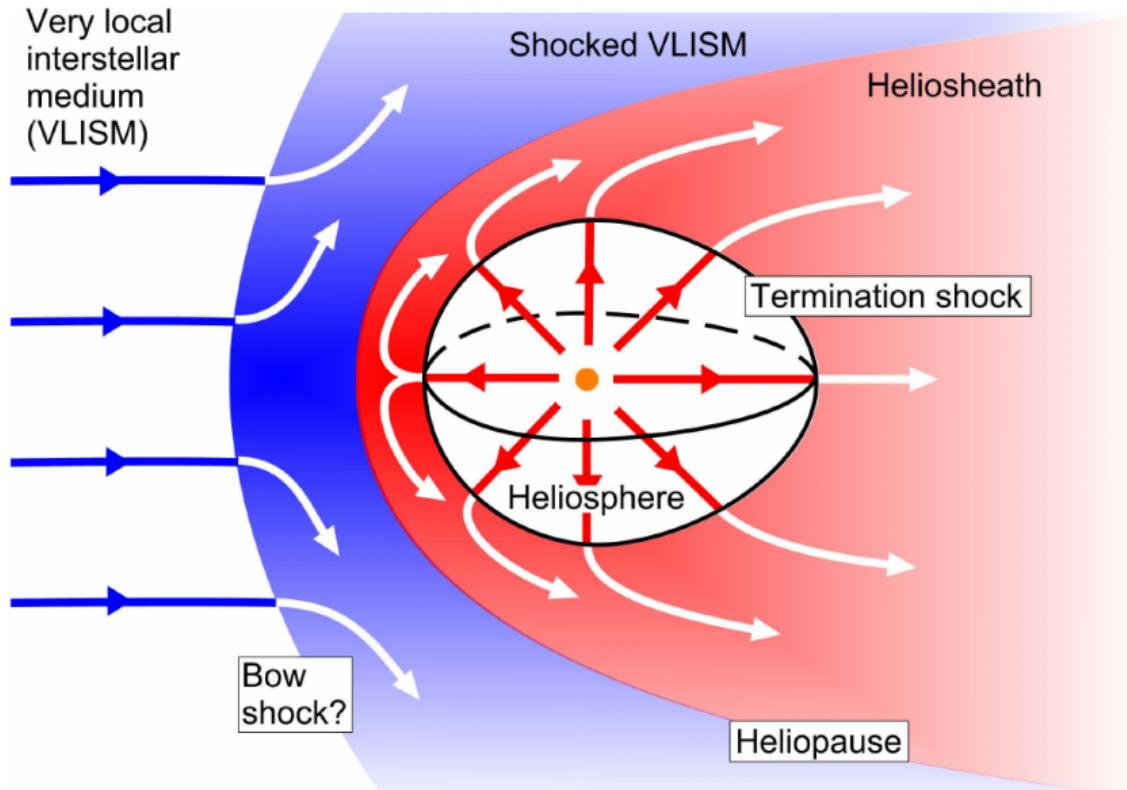


Solar wind model for the inner heliosphere



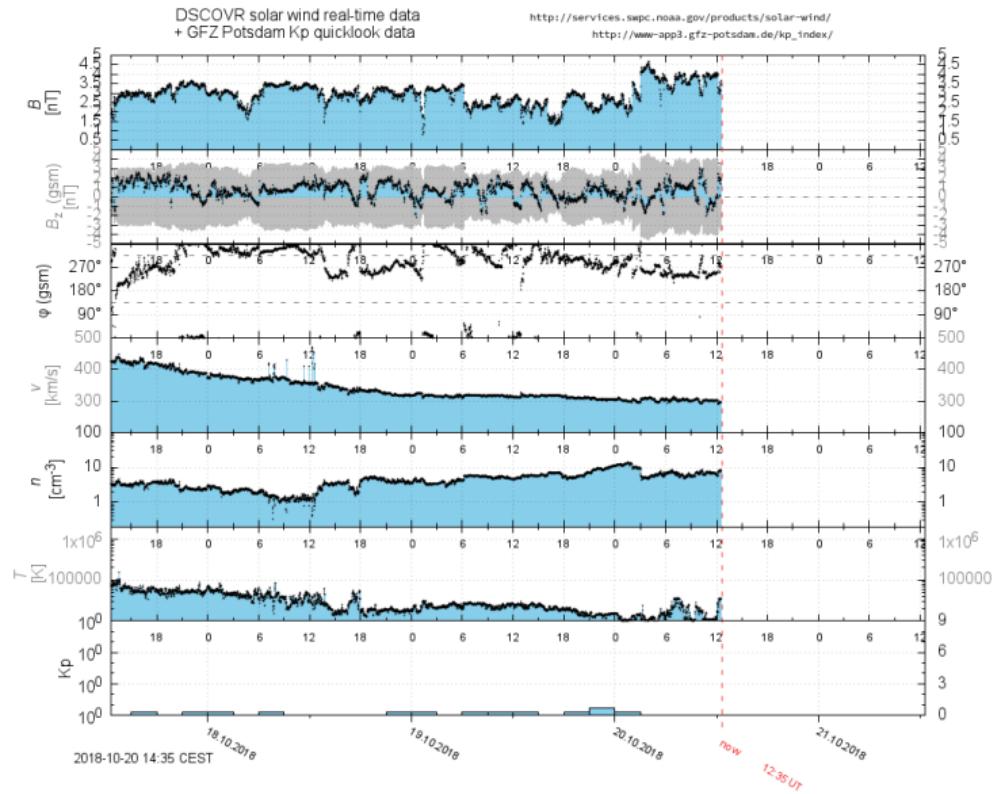
Courtesy of David Hathaway, Solar Cycle Science, 2018, updated version of Hathaway (2015, Fig. 17)

Solar wind



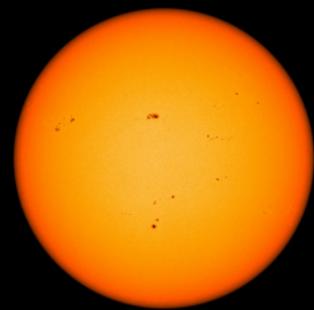
Credit: Owens & Forsyth (2013, Fig. 9)

Solar wind

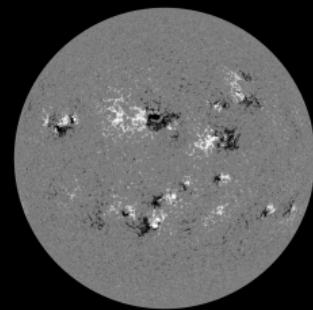


Solar surface and atmosphere

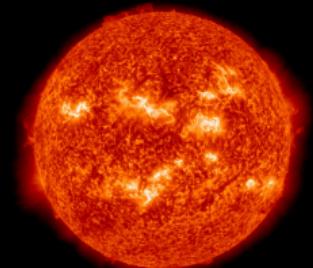
Intensitygram



Magnetogram



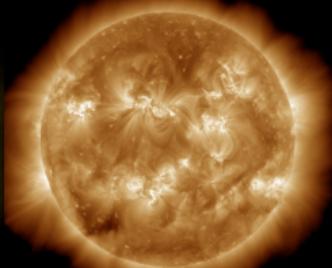
304 Å



171 Å

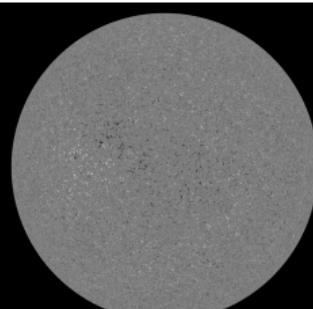
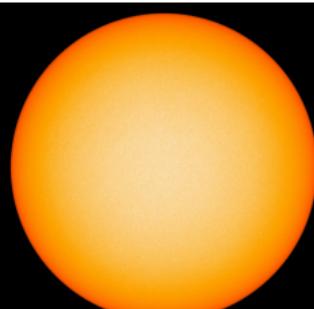


193 Å



Credit: NASA SDO/HMI, 16 May 2013

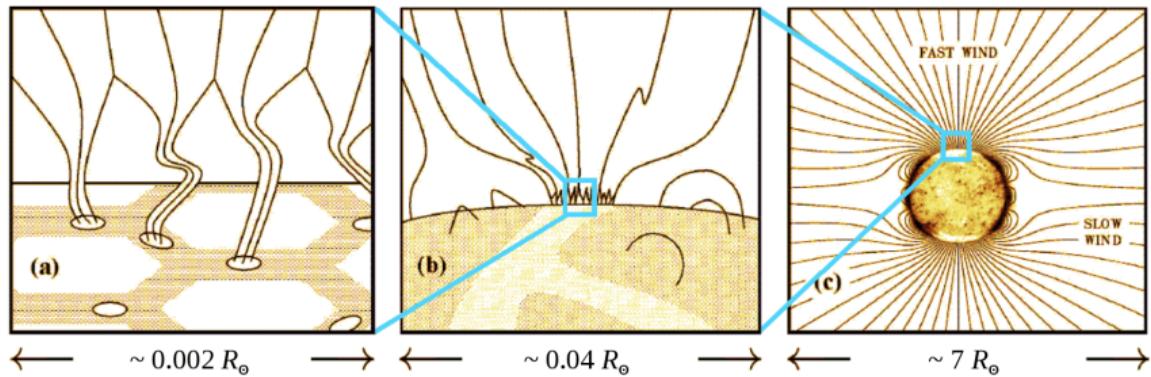
Credit: NASA SDO/AIA, 16 May 2013



304/193 304 2018-10-28 11:09:18 UT

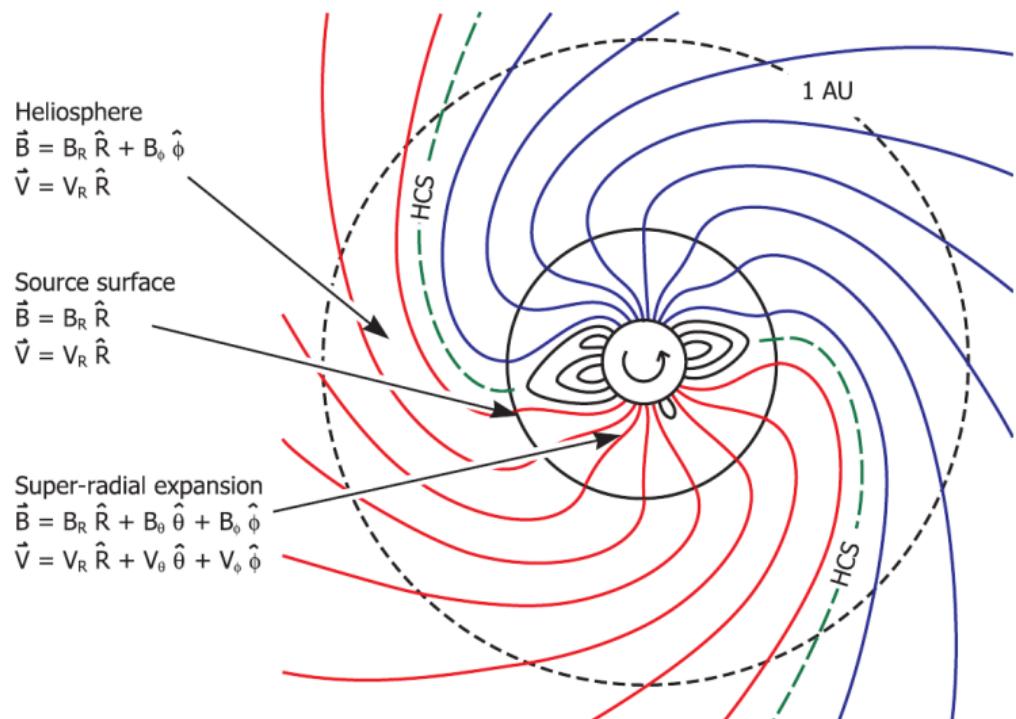
Credit: NASA SDO/AIA, 28 October 2018

Solar magnetic field



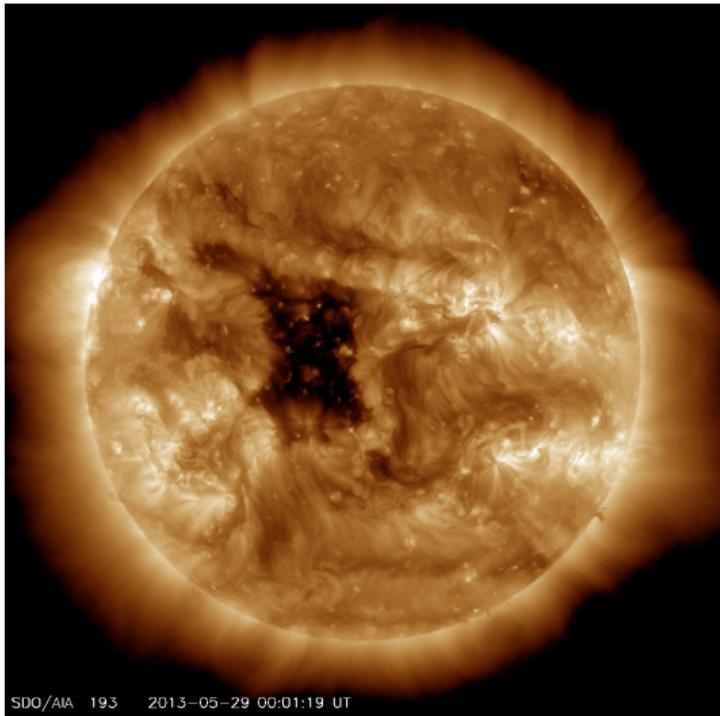
Courtesy of S. R. Cranmer

Solar magnetic field



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

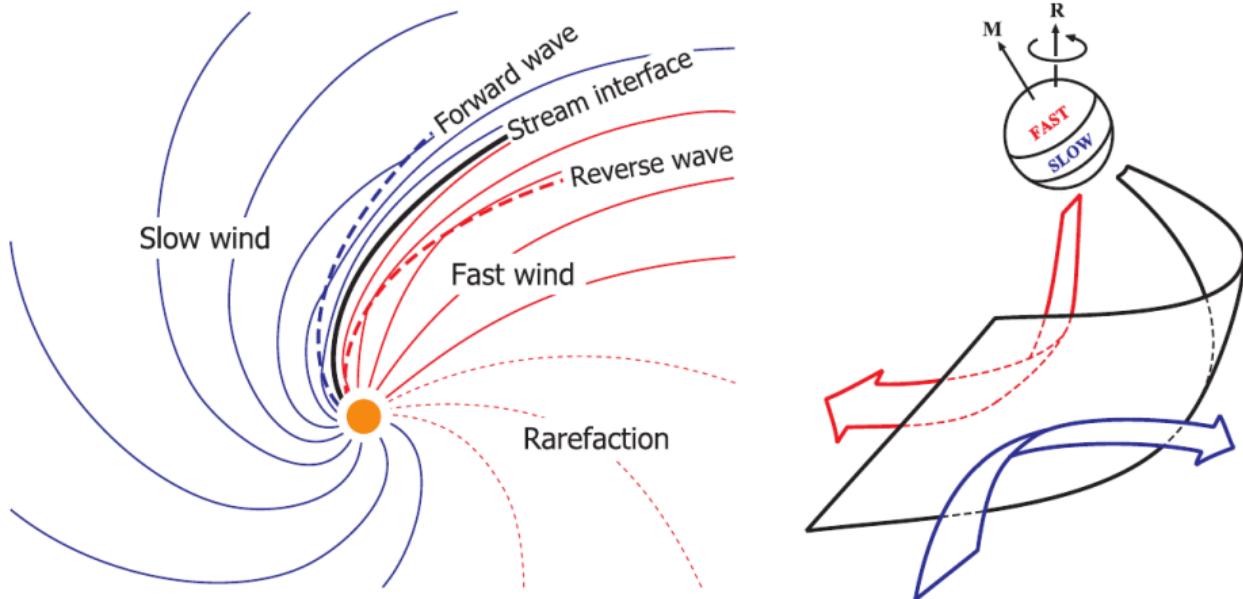
Slow and fast solar wind



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

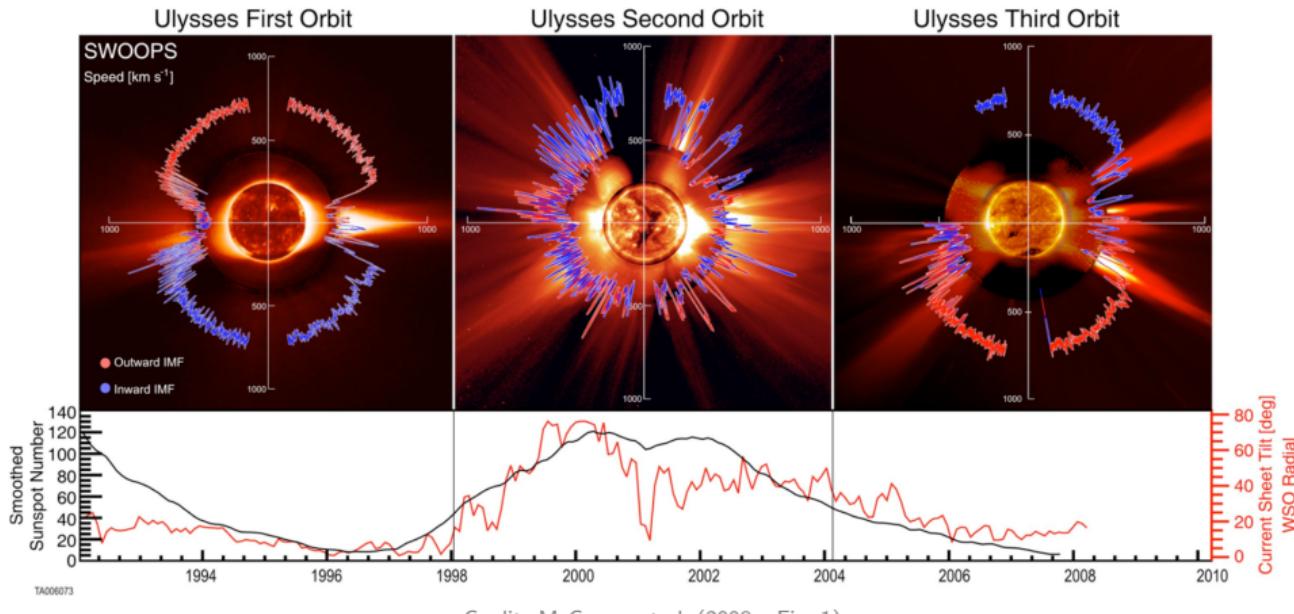
Credit: NASA/SDO and the AIA, EVE and HMI science teams

Slow and fast solar wind



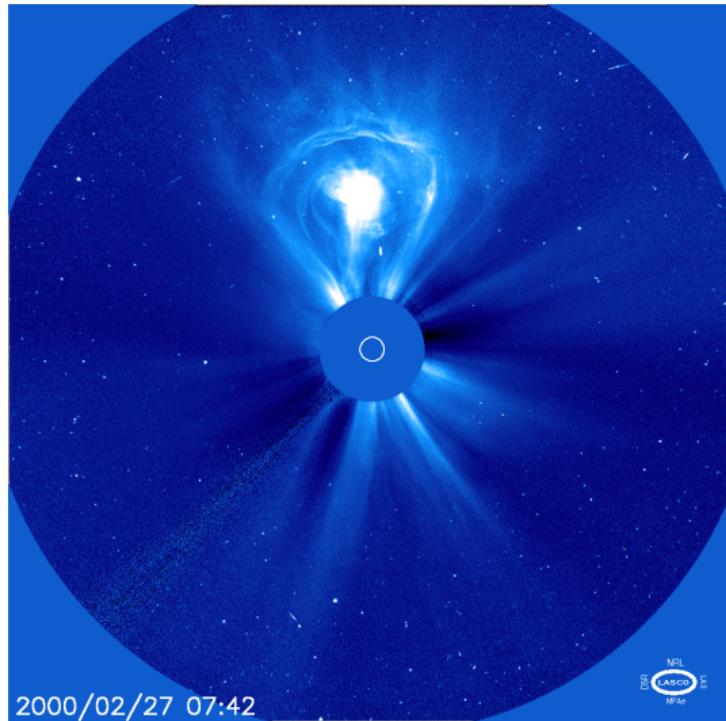
Credit: Owens & Forsyth (2013, Fig. 7); right panel adapted from Pizzo (1991, Fig. 2)

Solar activity



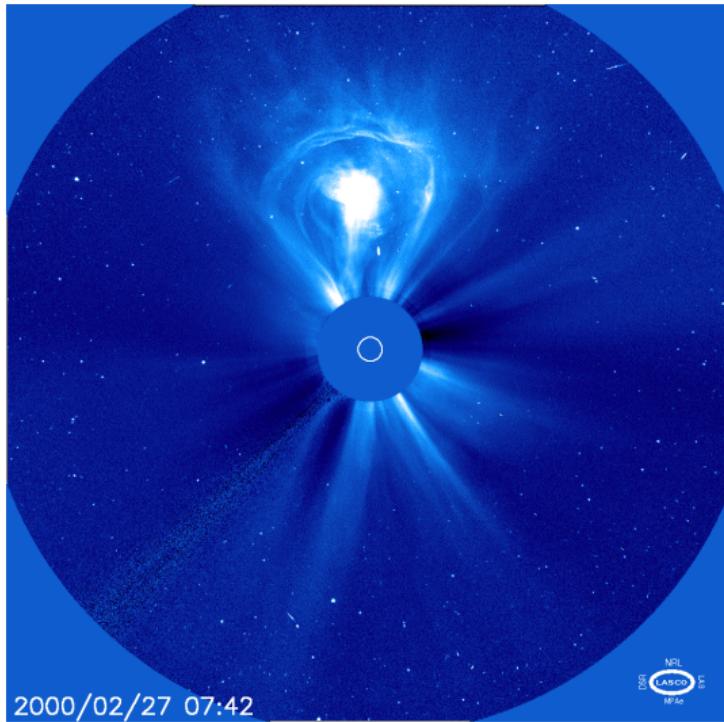
Credit: McComas et al. (2008a, Fig. 1)

Coronal mass ejections

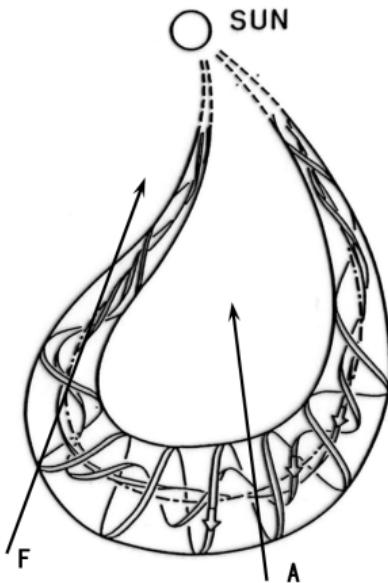


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

Coronal mass ejections

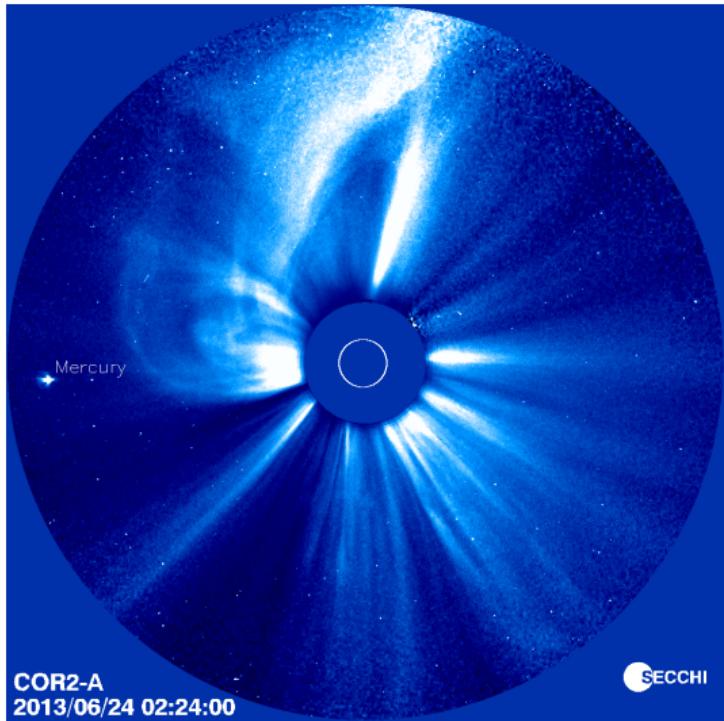


Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA

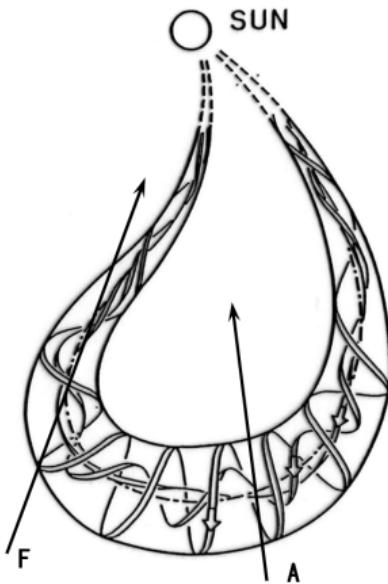


Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections

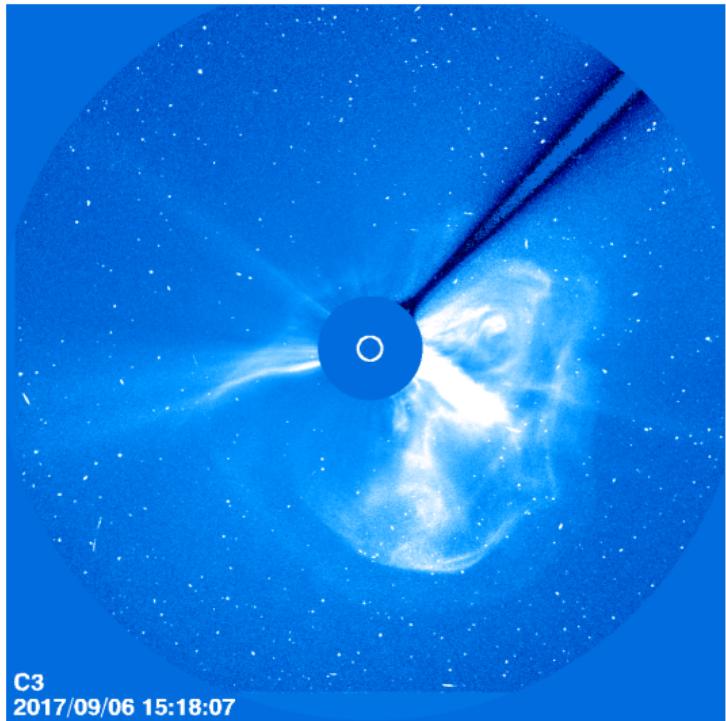


Courtesy of STEREO/COR2 consortium (NASA)



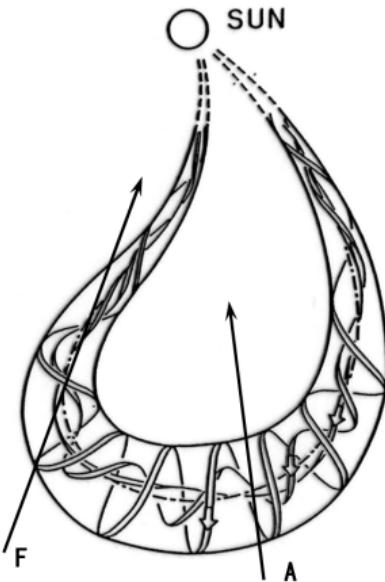
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

Coronal mass ejections



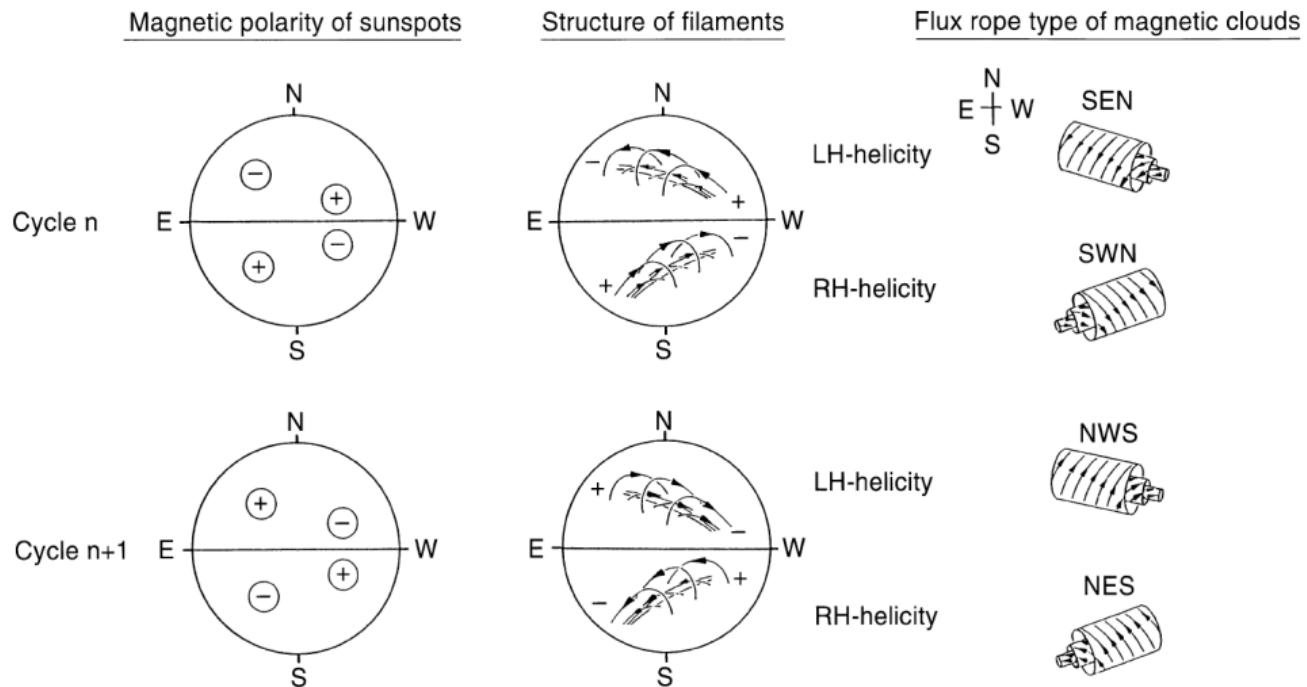
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2017/09/06 15:18:07

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



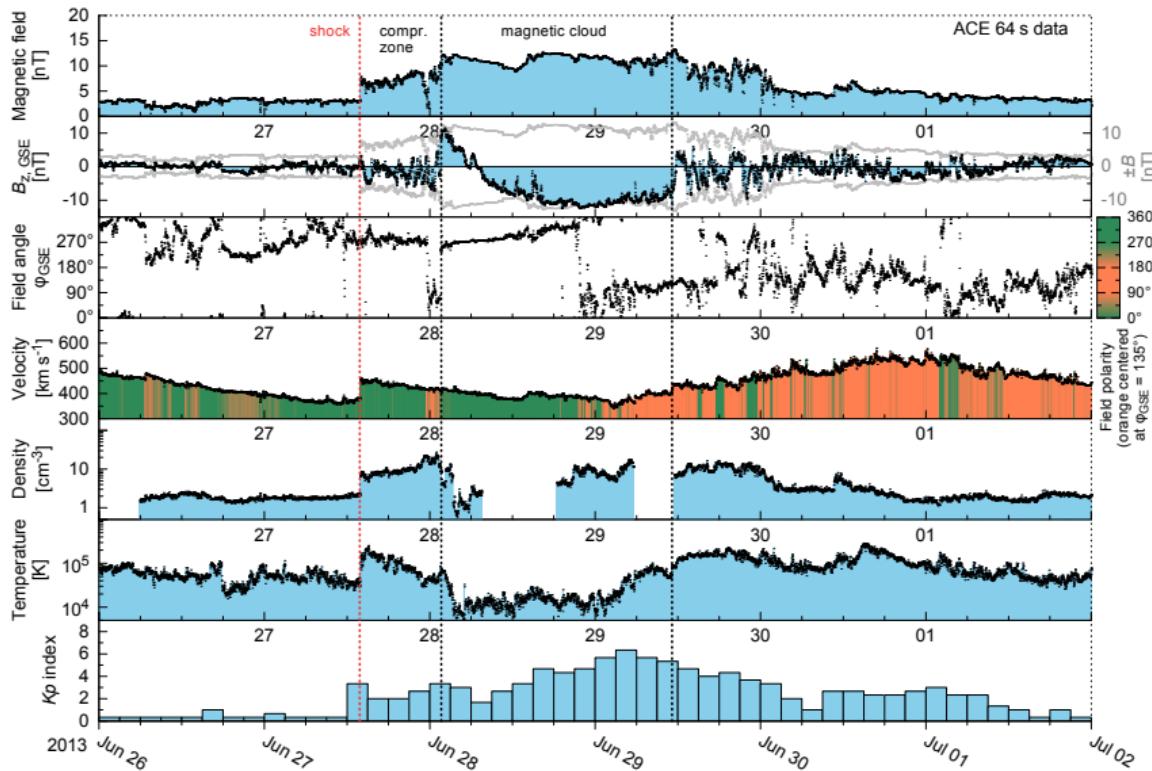
Credit: Marubashi & Lepping (2007, Fig. 1, panel (a))

CME orientation

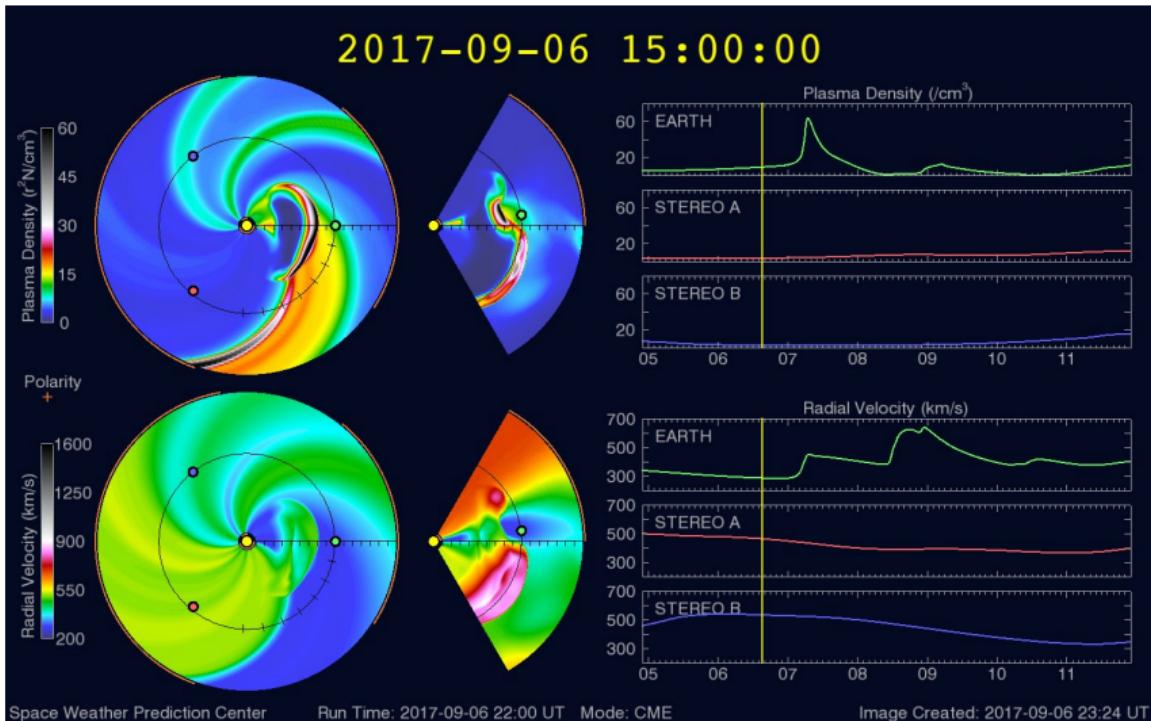


Credit: Bothmer & Schwenn (1998, Fig. 18)

In-situ CMEs

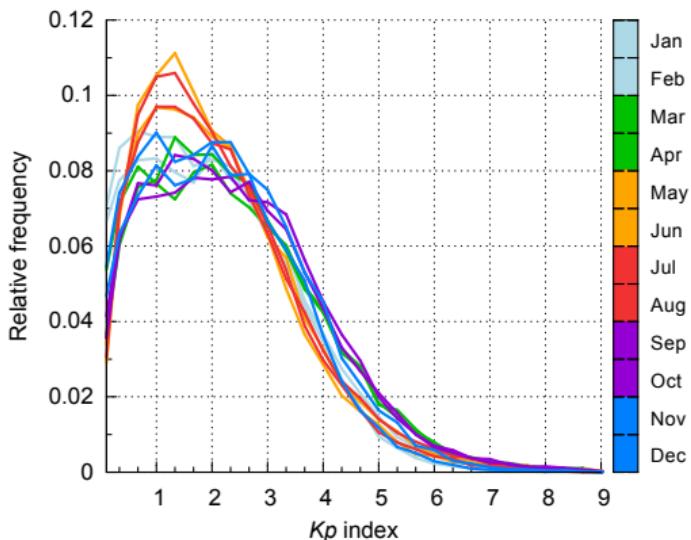
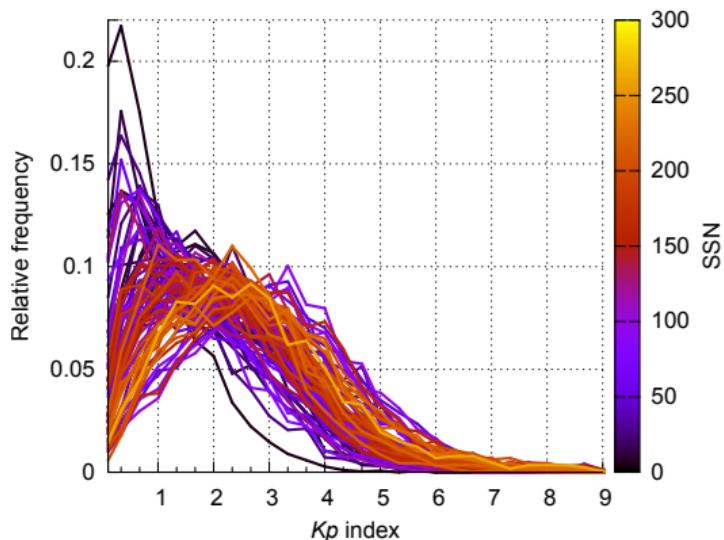


Solar wind and CME forecast

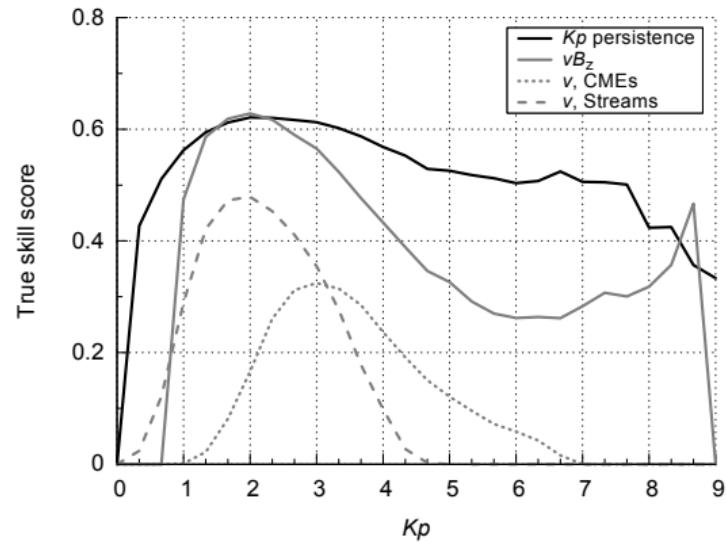
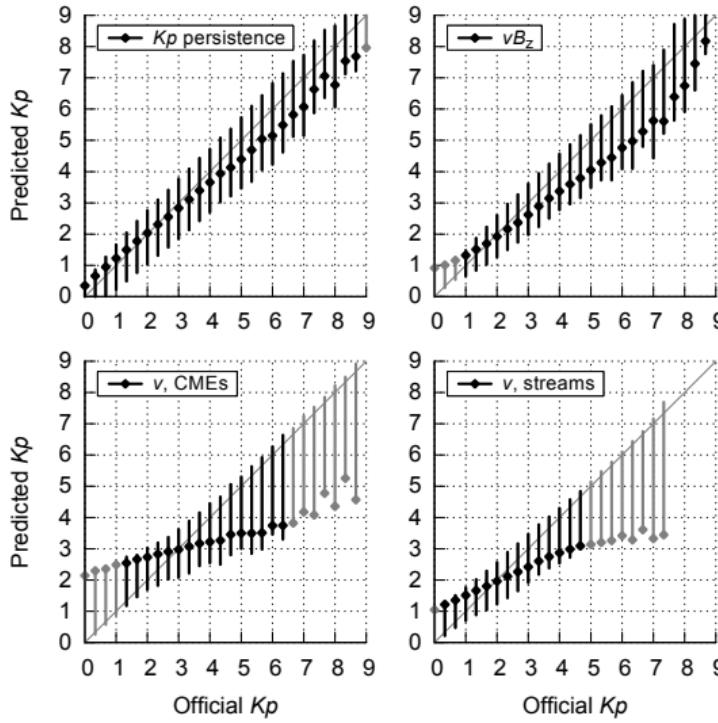


Credit: SWPC: WSA-Enlil Solar Wind Prediction. NOAA National Centers for Environmental Information

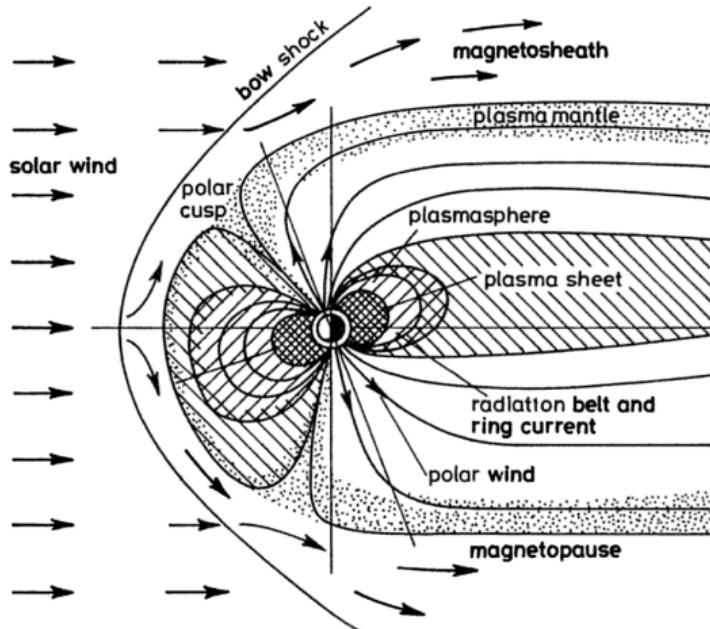
Kp long-term variations



Prediction performance



Magnetosphere

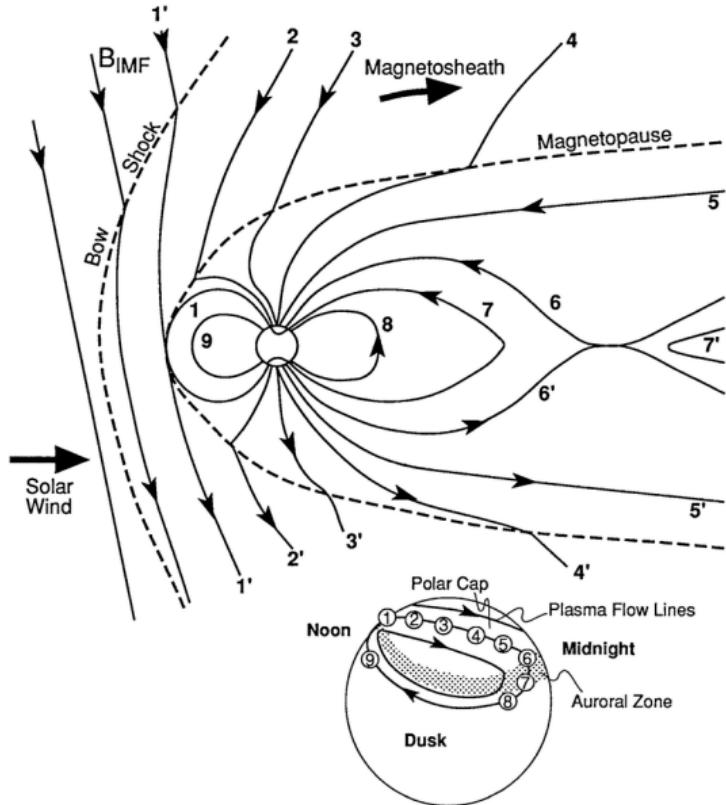


Credit: Davies (1990, Fig. 2.12)

Interaction mechanisms between solar wind and magnetosphere:

- Reconnection
- Turbulence
- Compression
- Induction

Magnetosphere



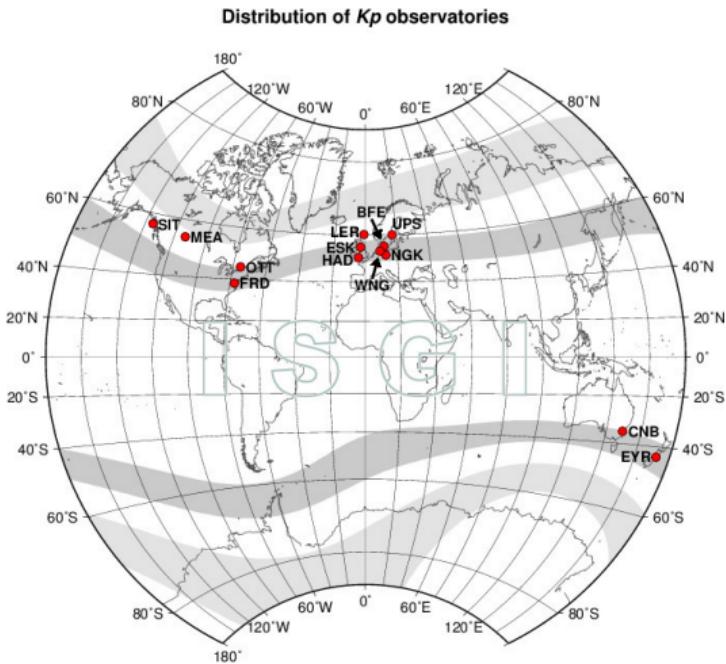
Credit: Hughes (1995, Fig. 9.11)

Factors that influence the reconnection flux rate:

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

Kp index

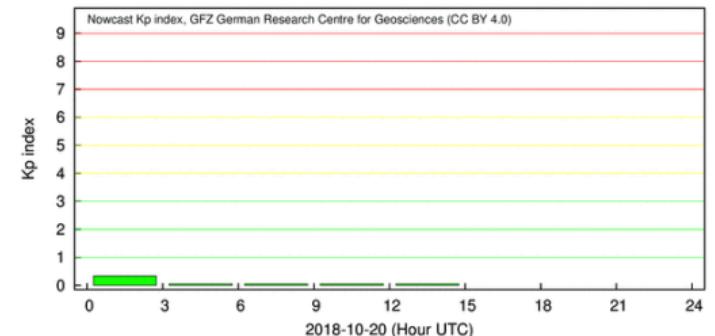
- Planetary geomagnetic disturbance indicator
- 3-hourly variation maxima
- 13 observatories at 50° geomagnetic latitudes
- Scale from 0 to 9



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

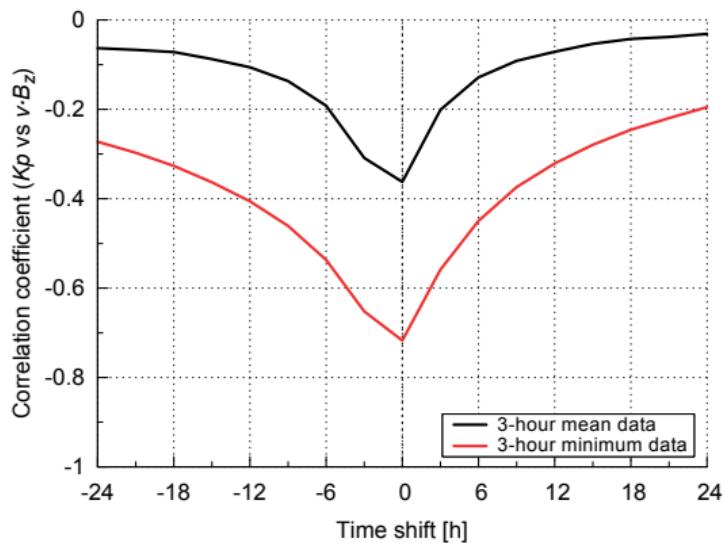
Kp index

Quicklook *Kp*

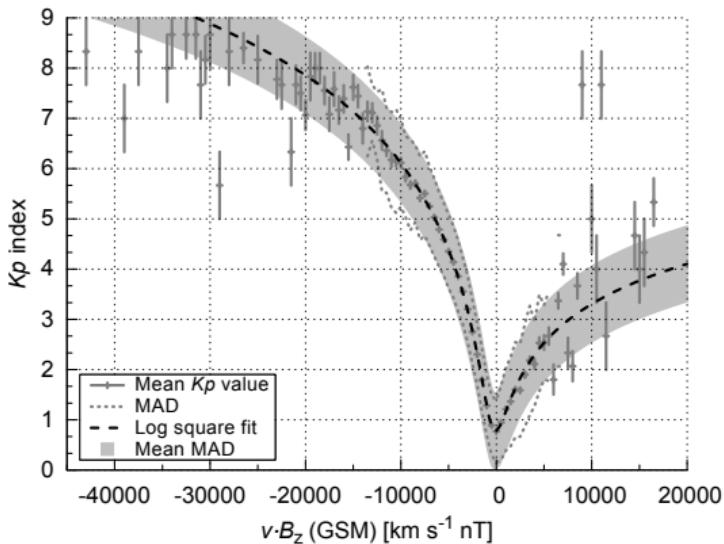
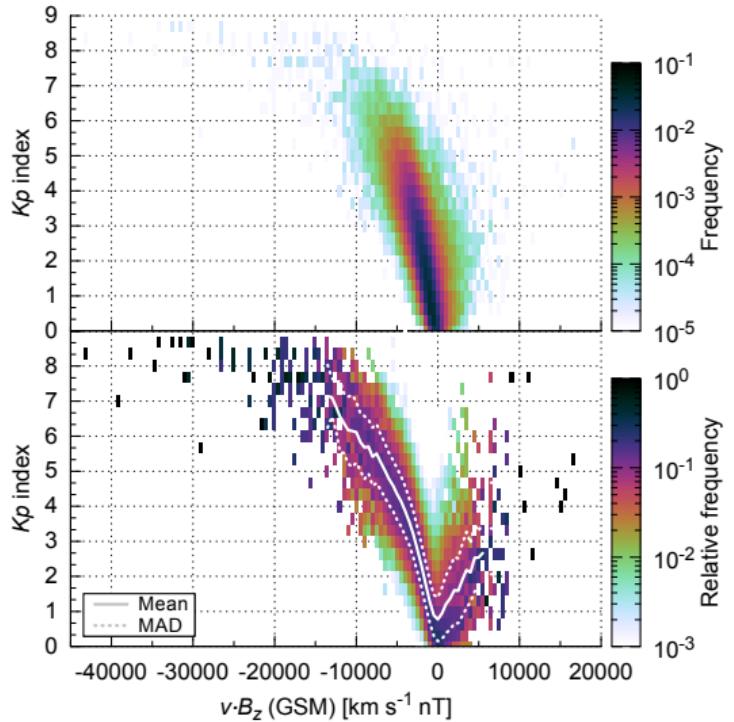


Credit: GFZ Potsdam, 2018

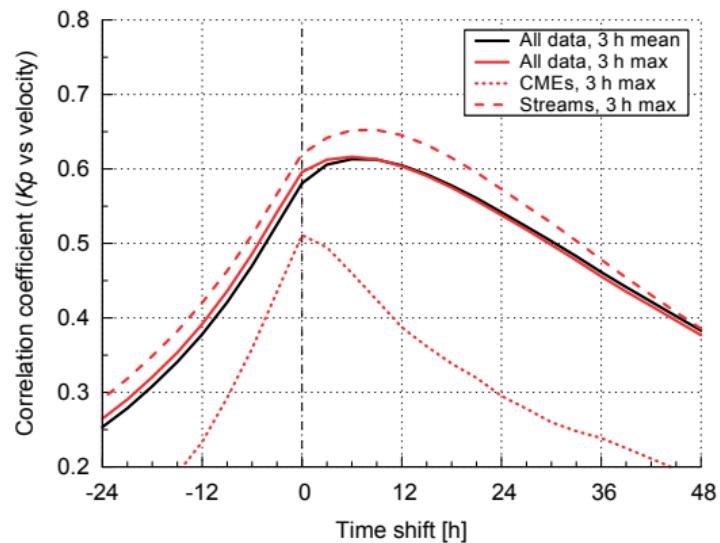
Solar wind electric field



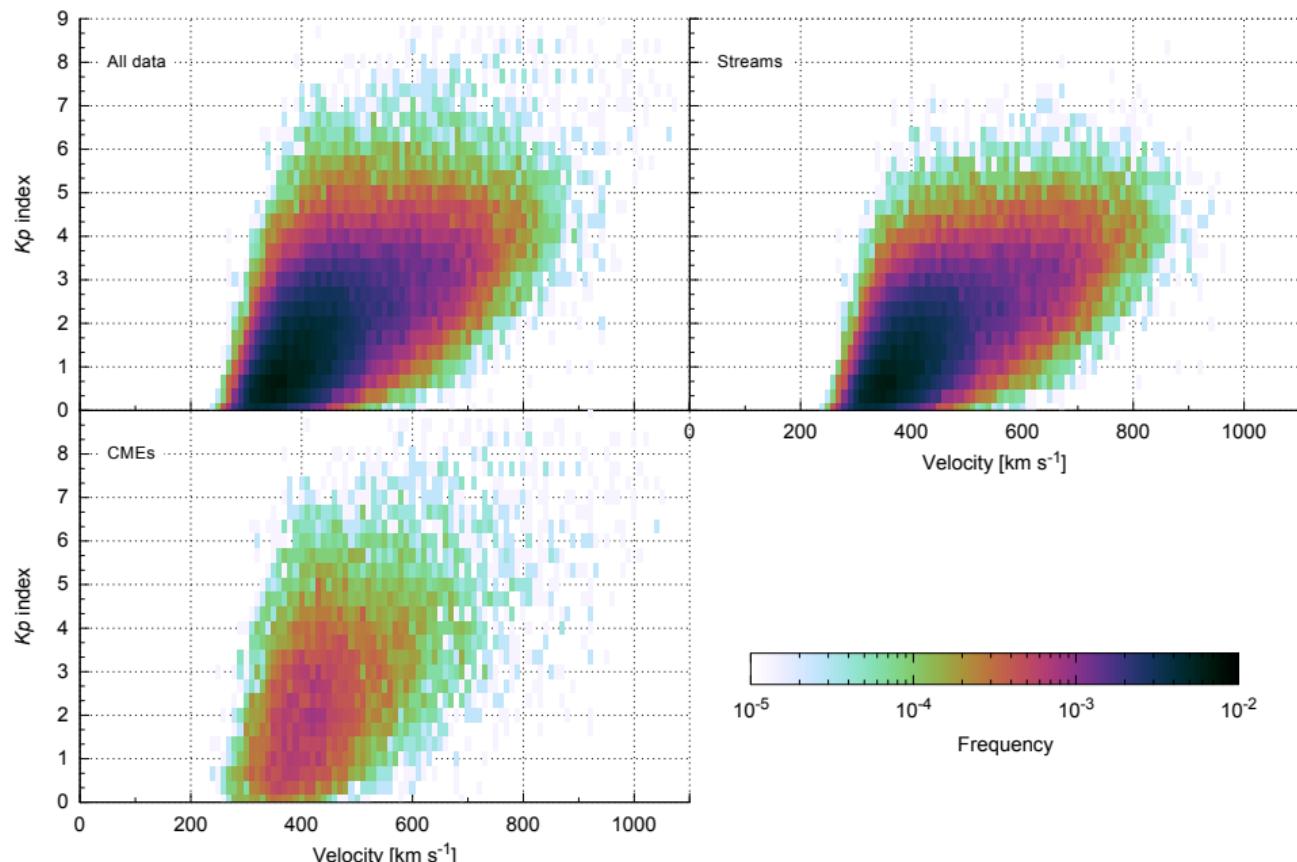
Solar wind electric field

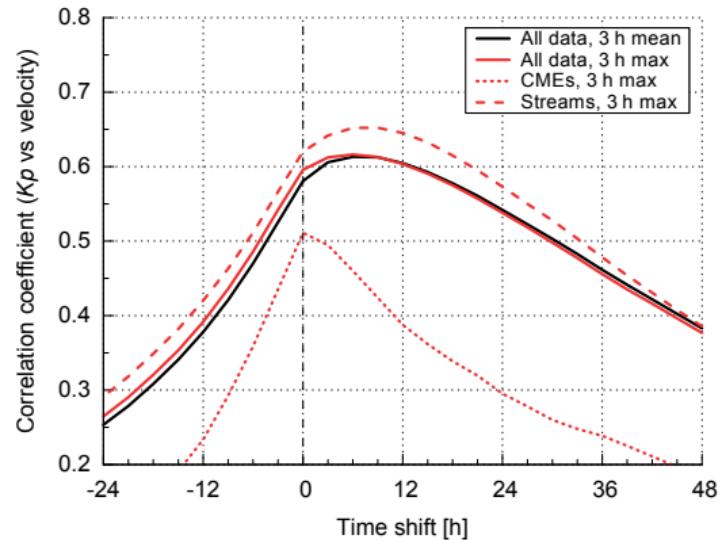


Solar wind velocity

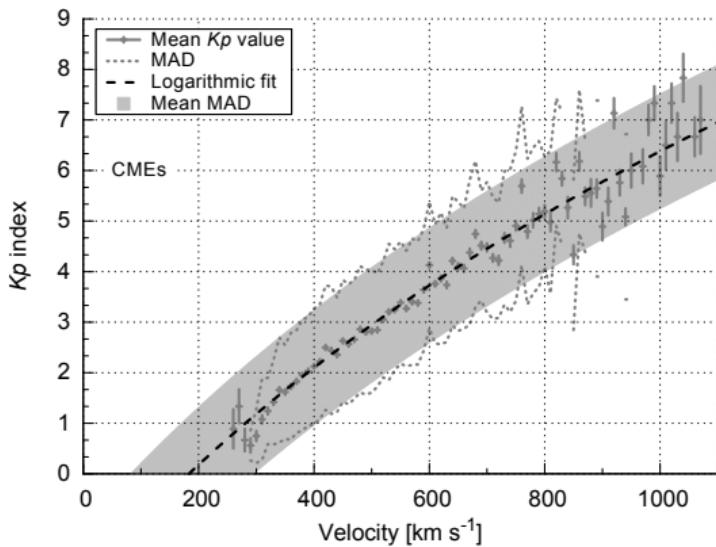
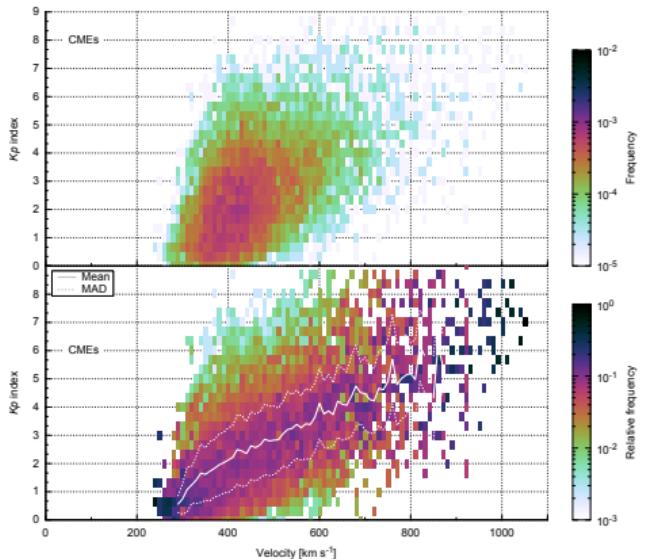


Solar wind velocity

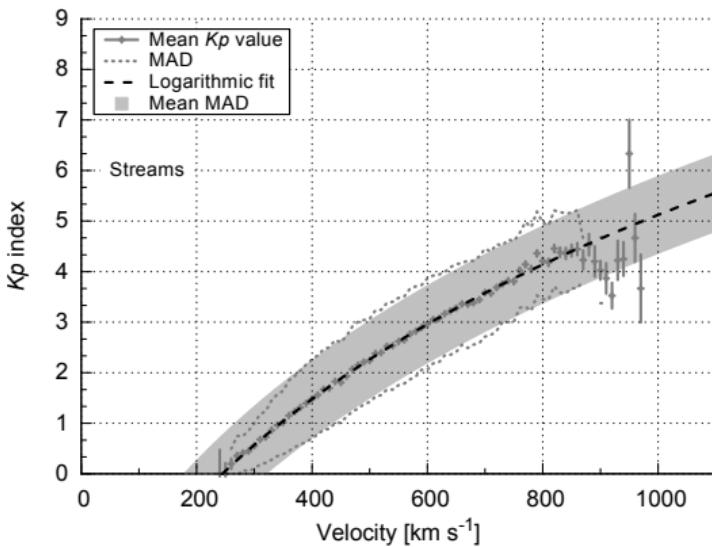
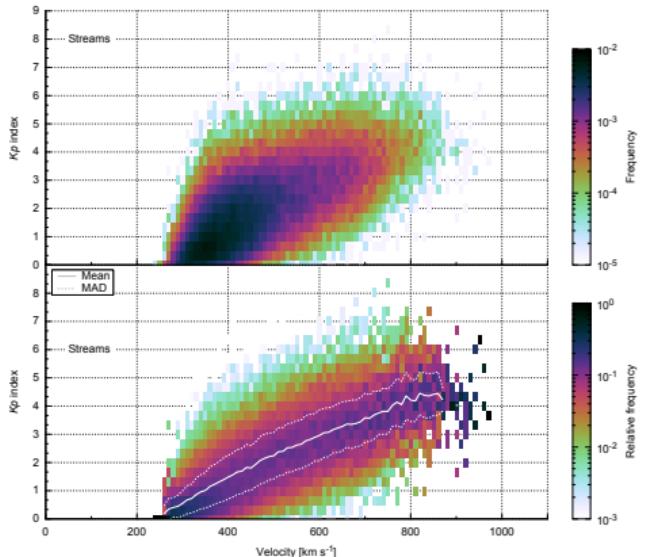


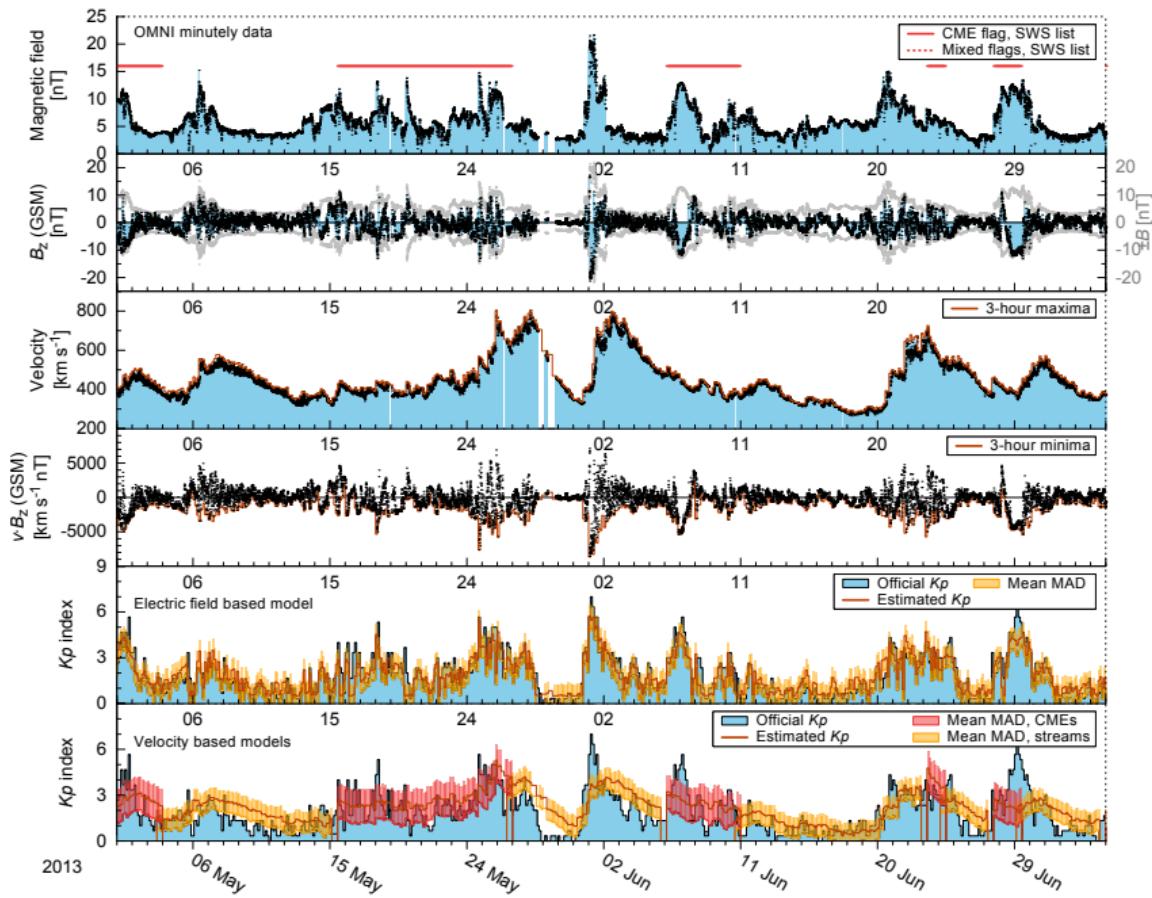


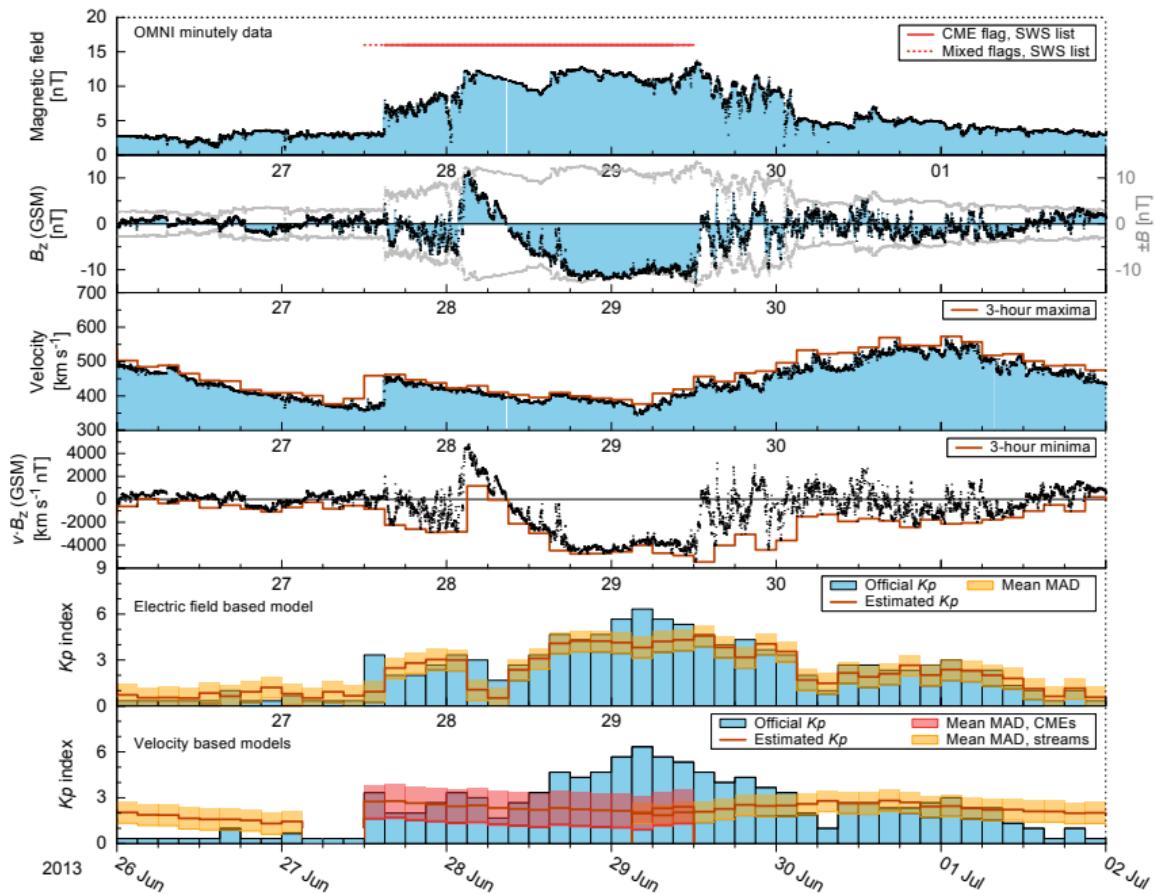
CME velocity



Stream velocity







Results

Predictive K_p models based on relations with

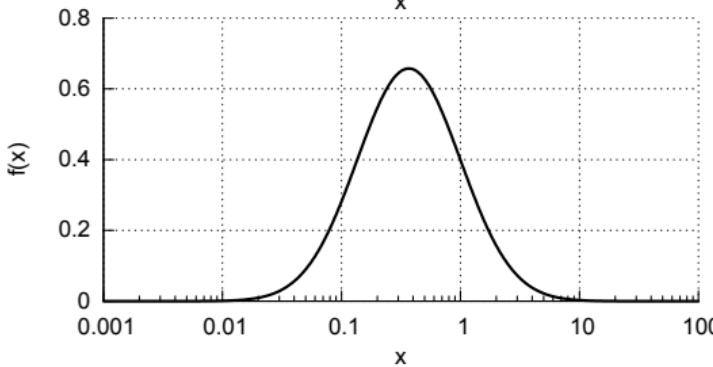
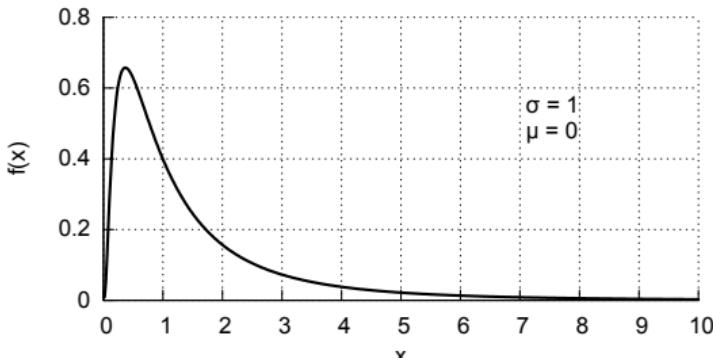
- Solar wind electric field proxy (vB_z)
- Velocity of CME-associated flows (v_{CME})
- Velocity of solar wind streams (v_{stream})

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:

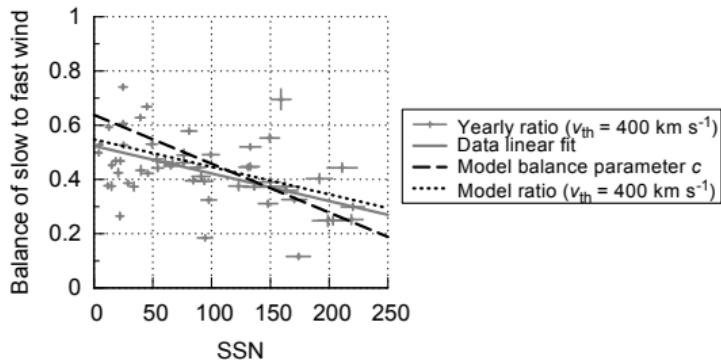
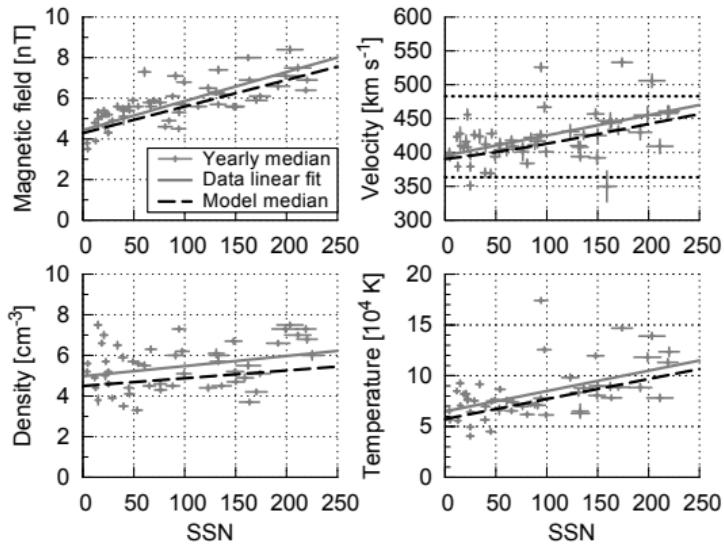
$$x_{\text{med}} = \exp(\mu), \quad x_{\text{avg}} = \exp\left(\mu + \frac{\sigma^2}{2}\right)$$

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

Unsolved problems:

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

Solar activity



PSP perihelia prediction

