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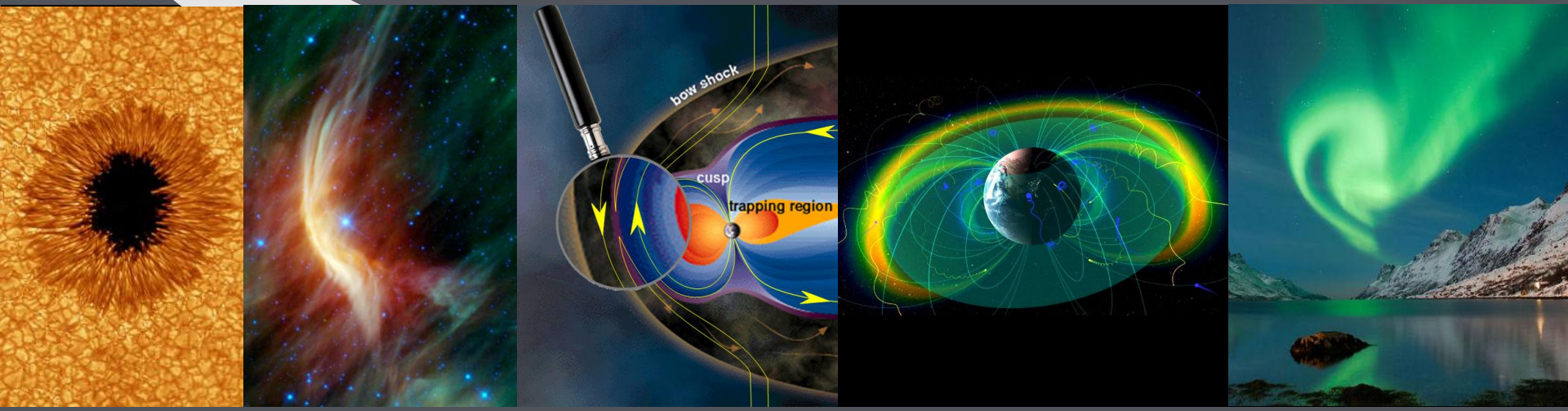


Quantifying solar wind-magnetosphere coupling on a range of timescales

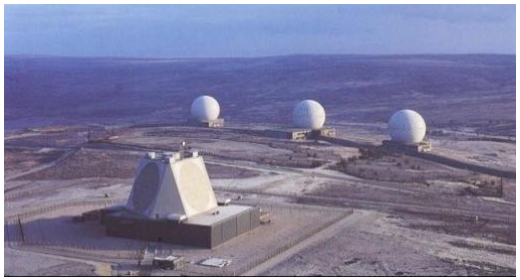
ISWI - SCOSTEP/COURSE online seminar

25th November, 2026

Forecasting Space Weather







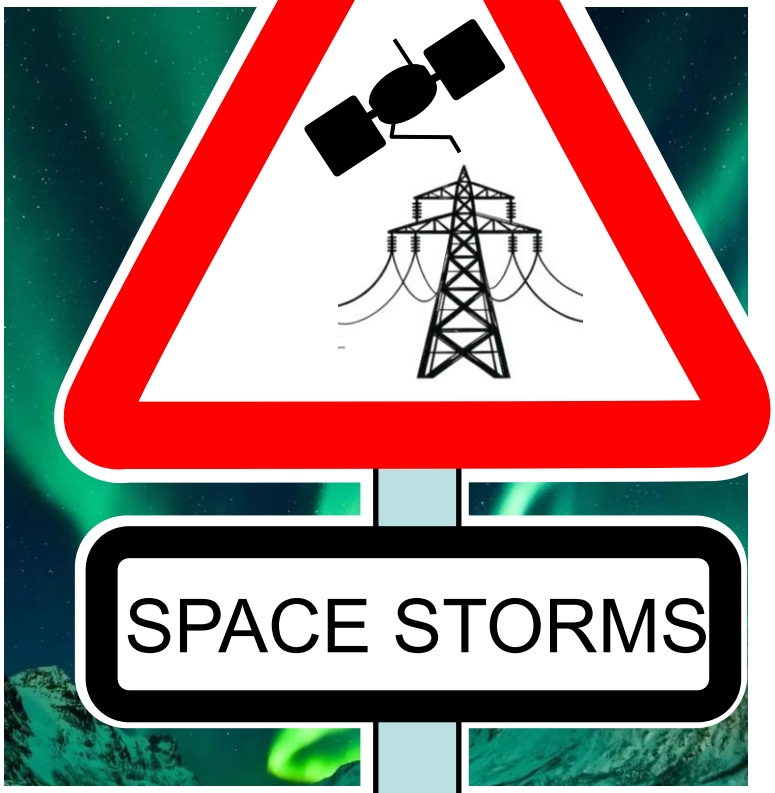








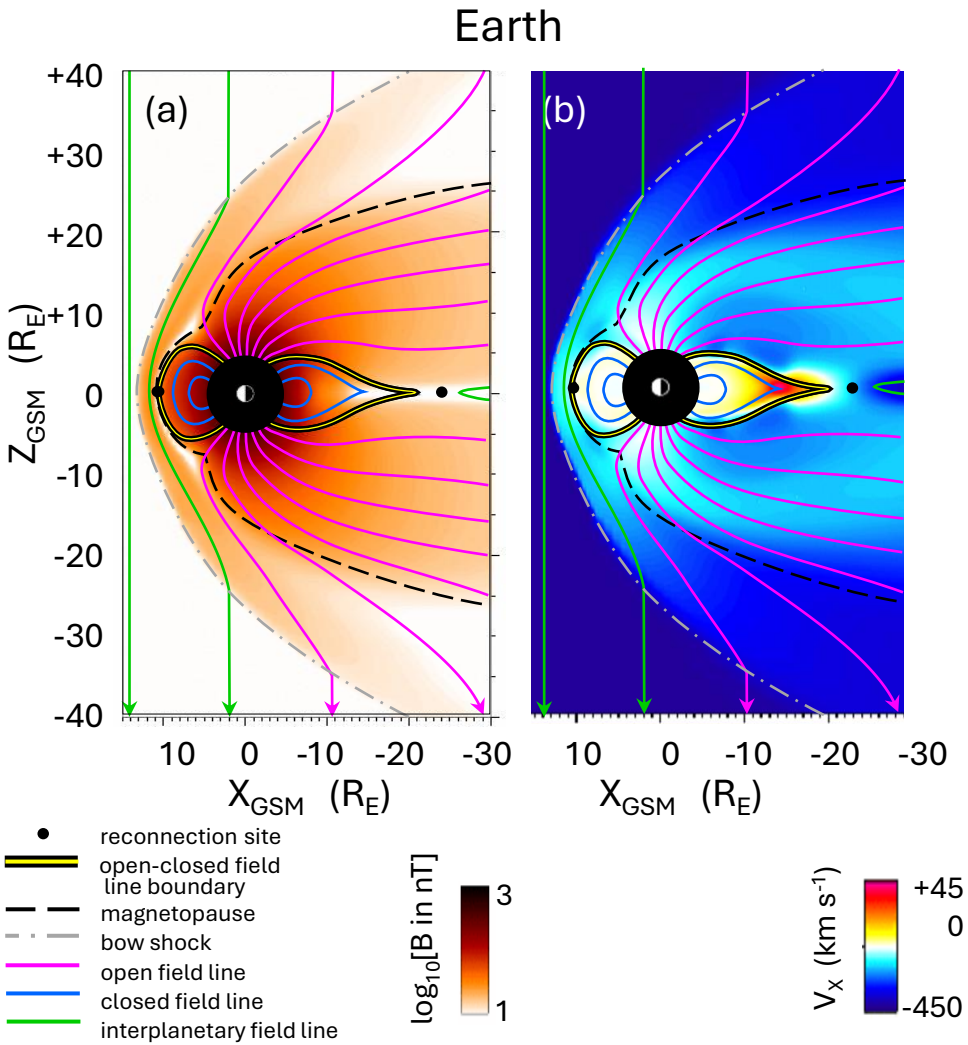


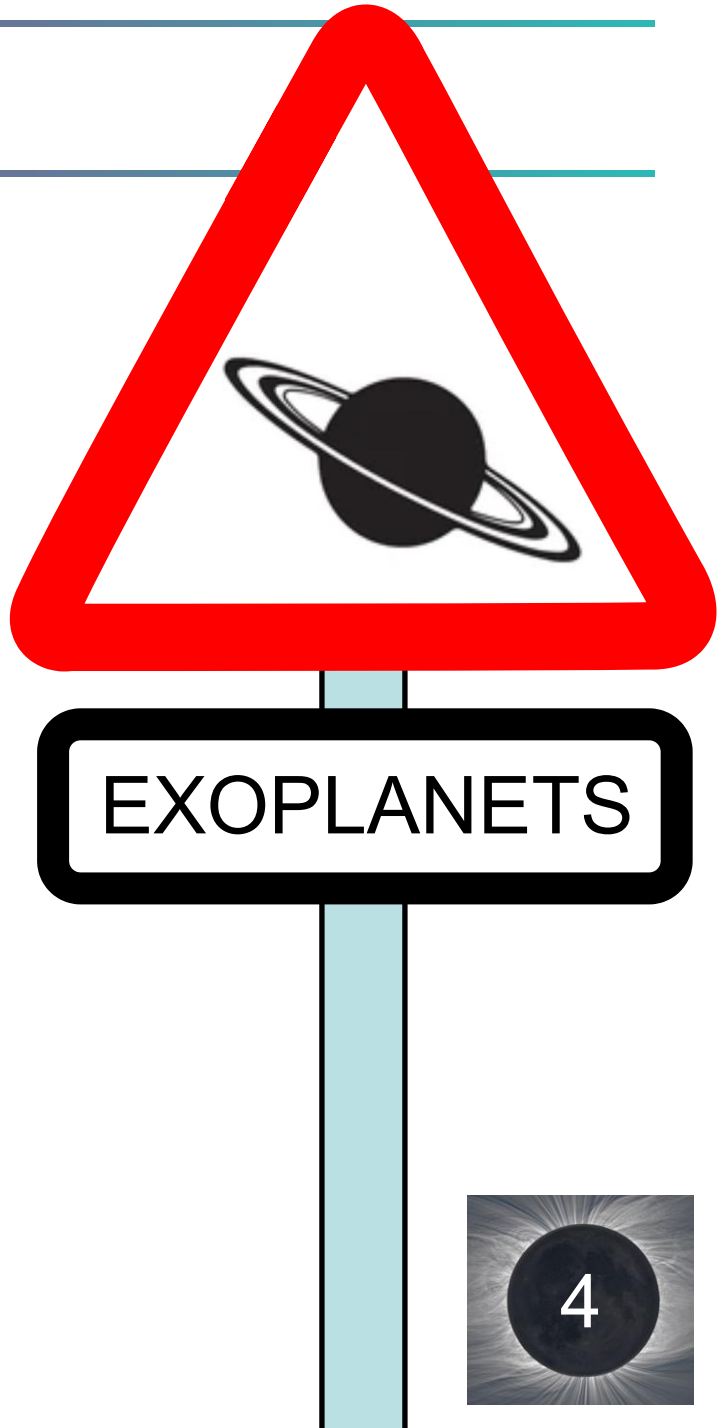






Exoplanet Research





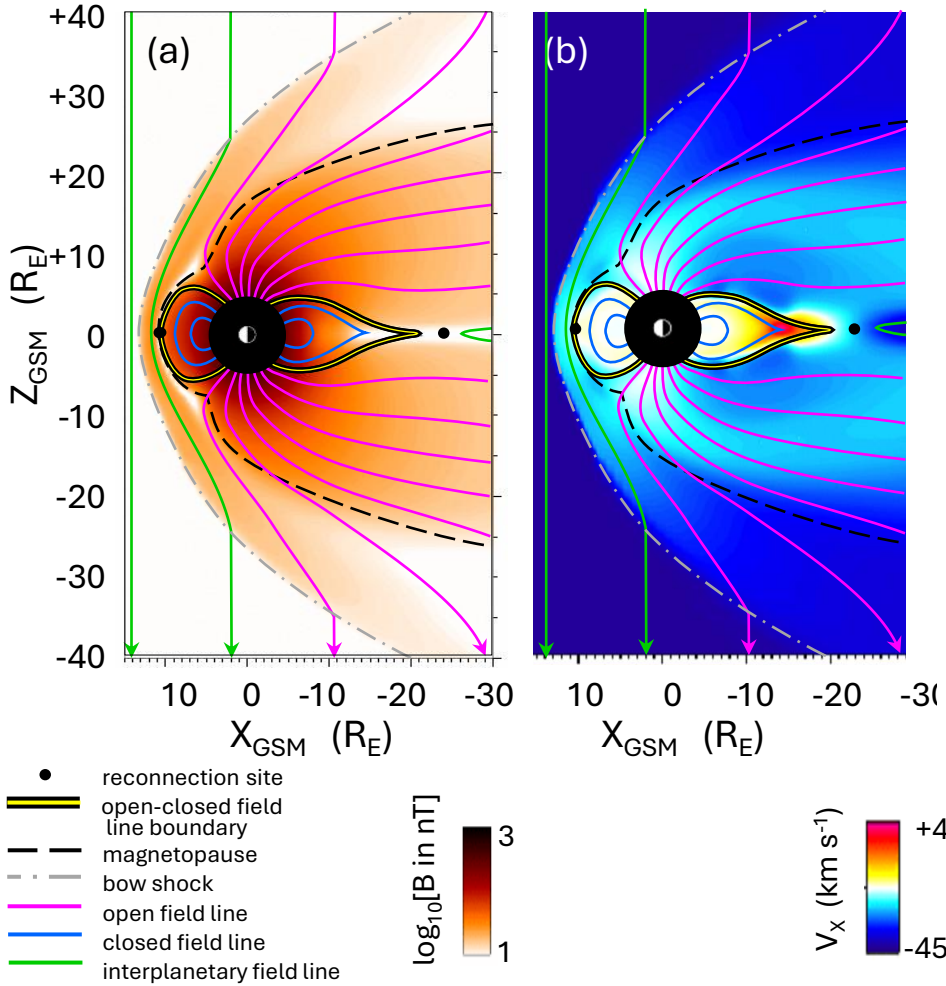
Lockwood, JGR, 2023, doi: 10.1029/2023JA031671

Exoplanets & Earth

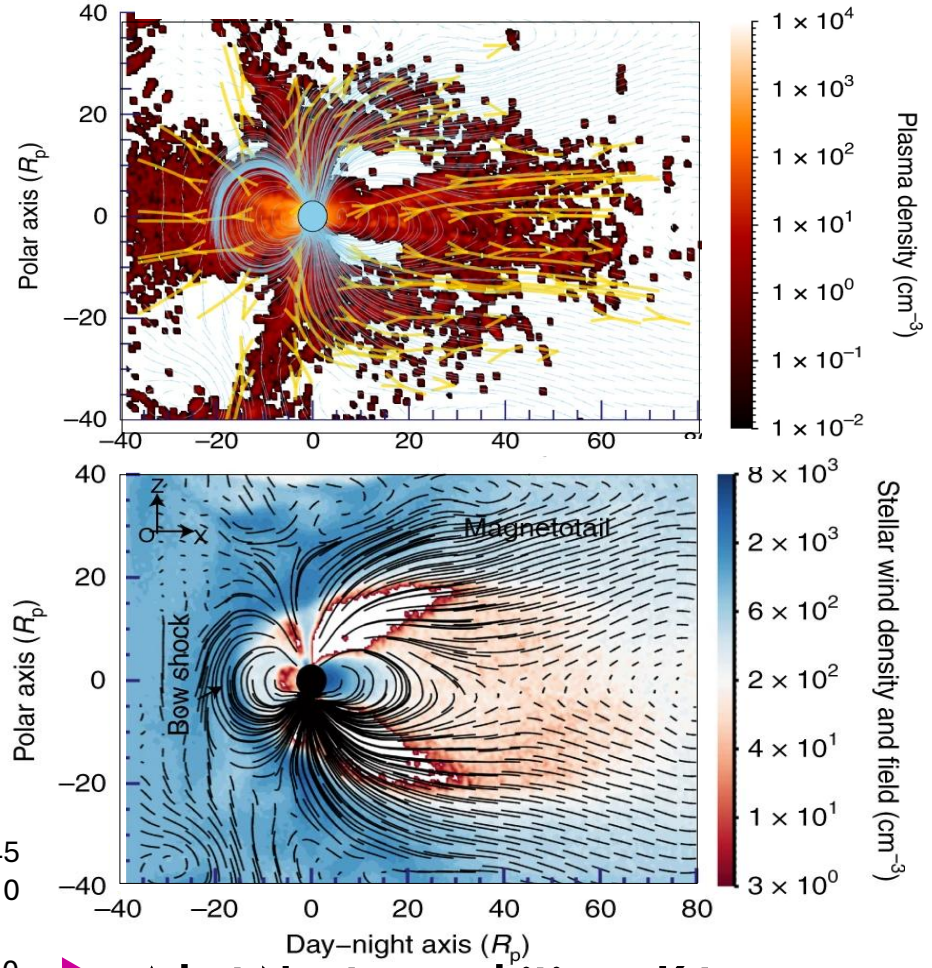
Royal Astronomical Society

University of Reading

Earth



HAT-P-11 b (Kepler-3b)

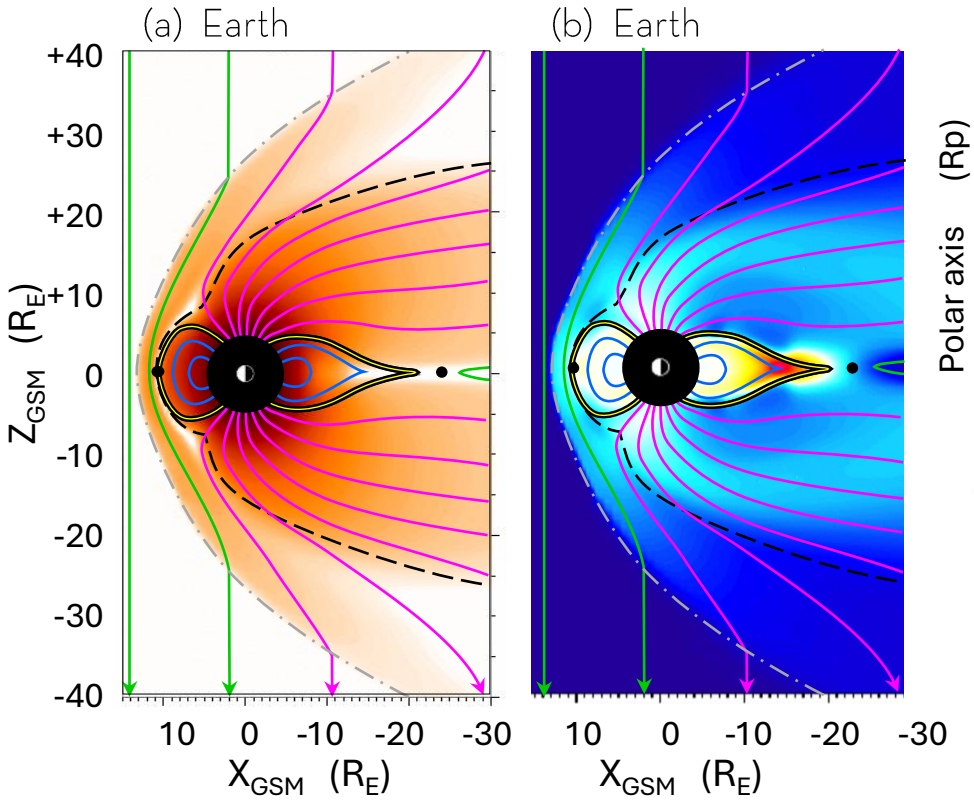


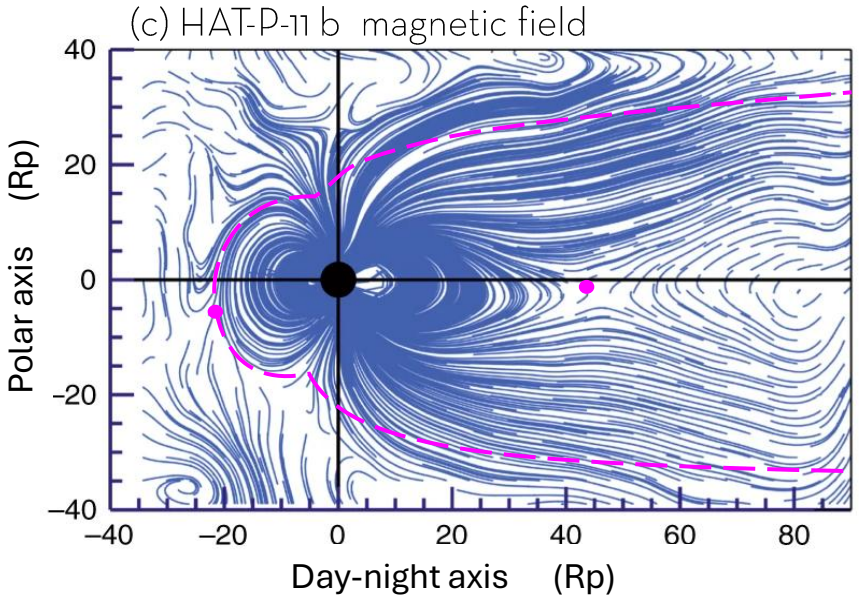
▶ **A hot Neptune orbiting a K-type star 38 parsecs away**

Lockwood, JGR, 2023, doi: 10.1029/2023JA031671

Ben-Jaffel et al., Nature Astron. (2022) doi: 10.1038/s41550-021-01505-x

Exoplanets & Earth





- **Based on pressure balance, magnetopause location and flux defined as open**
- **Assumes a planet-centric dipole intrinsic magnetic field**
- **Could determine field form with SKA data! Could see paleo- field reversals and their magnetospheric effects!!!**

Lockwood, JGR, 2023, doi: 10.1029/2023JA031671

Ben-Jaffel et al., Nature Astron. (2022) doi: 10.1038/s41550-021-01505-x



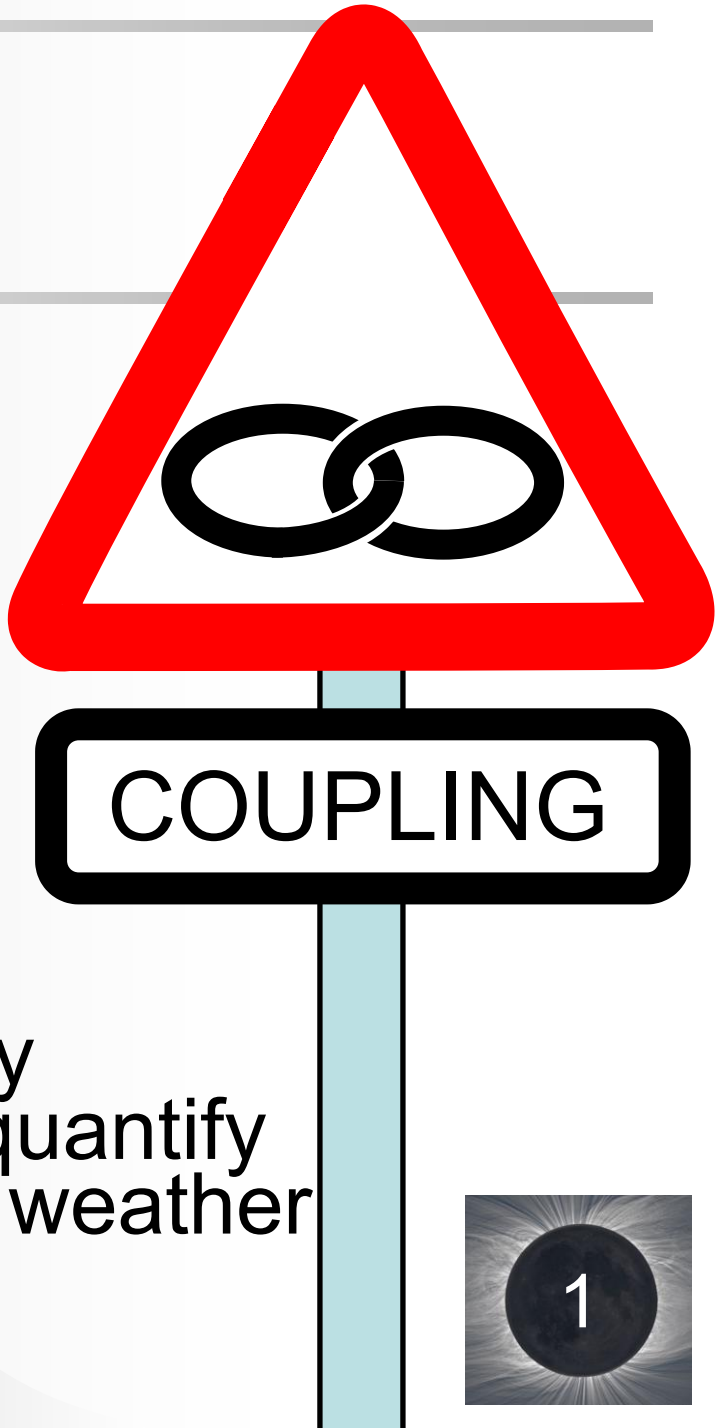
- My Definition

solar wind–magnetosphere coupling function

/ˈkʌp(ə)lɪŋ ˈfʌŋkʃ(ə)n/

(*compound noun*)

A combination of interplanetary parameters designed to best quantify and predict **a** terrestrial space weather disturbance indicator or index





Coupling functions

- Great many proposed since first correlations of terrestrial and interplanetary observations
- Theory-based

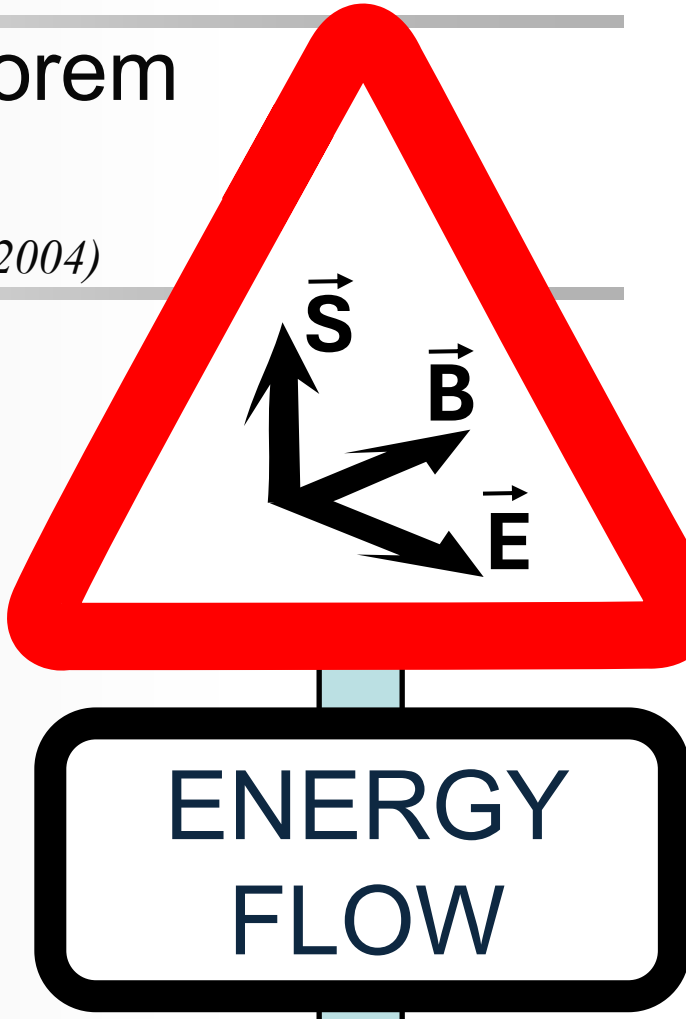
  (i) power input

  (ii) voltage applied
- **Or** based on empirical correlations
- **Or** based on theory with empirically-derived factors
- **Or** from numerical global simulations
- **But** there are pitfalls in both derivation and testing



Poyntings theorem for a plasma

(Cowley, 1991, Lockwood, 2004)



- The high electrical conductivity and fluid nature of a plasma means that Poynting's theorem reduces to

$$-\partial W_B/\partial t = \int_A \vec{S} \,.\, d\vec{A} + \int_\tau \vec{E} \,.\, \vec{J}\; d\tau$$

where W_B is the energy density stored in the magnetic field, $\vec{S} = (\vec{E} \times \vec{B})/\mu_o$ the Poynting flux (the flux of electro-magnetic energy) , $\vec{E}$ the electric field, $\vec{J}$ the current density & A is the surface area of the volume τ

- i.e.

$$\left\{\begin{array}{c}\text{Energy taken}\\ \text{from the}\\ \text{magnetic field}\end{array}\right\} = \left\{\begin{array}{c}\text{Divergence}\\ \text{of Poynting}\\ \text{flux}\end{array}\right\} + \left\{\begin{array}{c}\text{Ohmic}\\ \text{heating of}\\ \text{particles}\end{array}\right\}$$

- In steady state $\partial W_B/\partial t = 0$

$\vec{E} \,.\, \vec{J} > 0$ is a sink of Poynting flux S (energy goes to particles)
& $\vec{E} \,.\, \vec{J} < 0$ is a source of S (energy is extracted from particles)

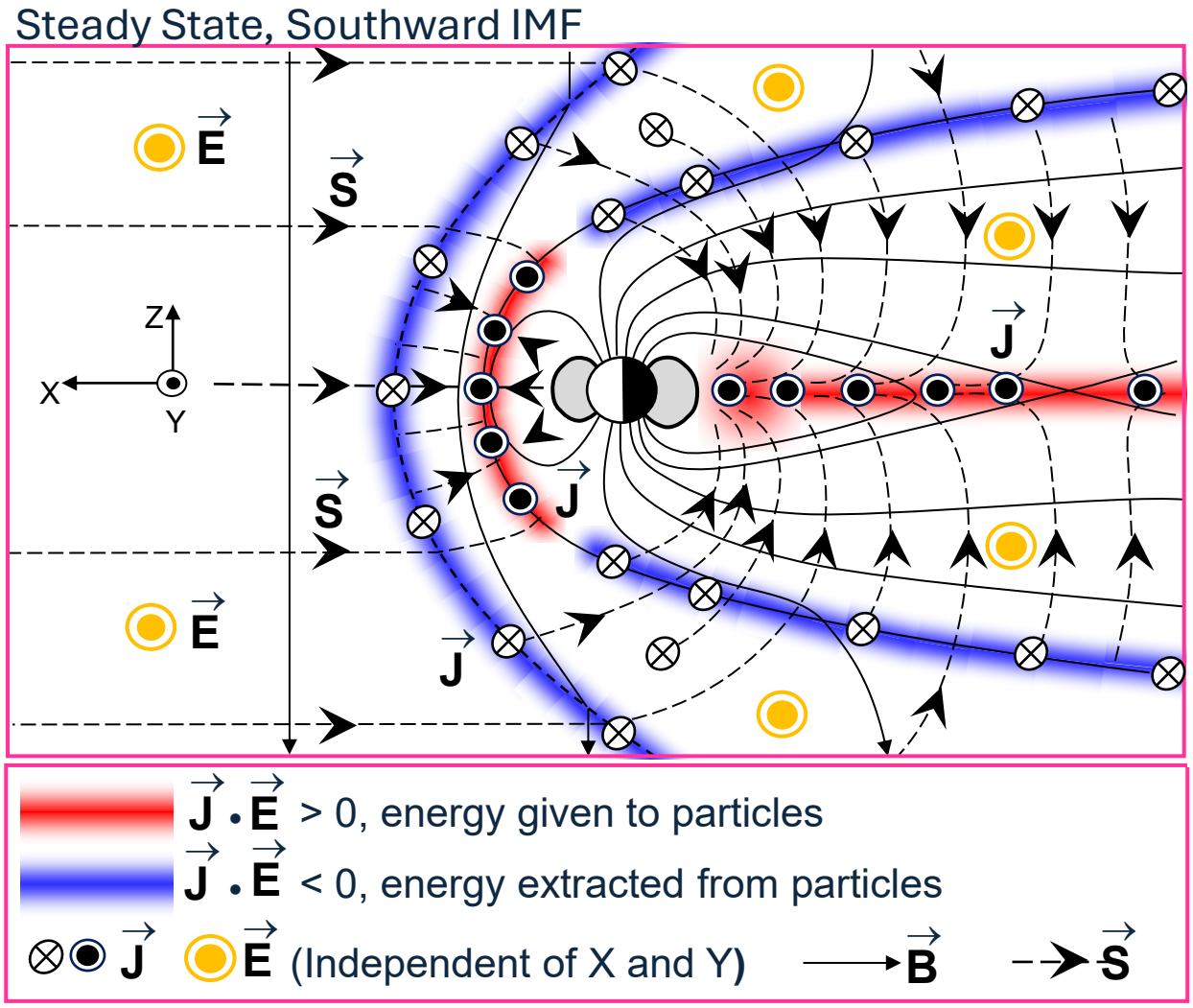
- In current free regions $\vec{E} \,.\, \vec{J} = 0$

$\partial W_B/\partial t > 0$ is a sink of S (energy goes into the magnetic field)
& $\partial W_B/\partial t < 0$ is a source of S (energy is extracted from the field)



Steady-state energy flow in the magnetosphere ($\partial W_B/\partial t = 0$)

(Cowley, 1991, Lockwood, 2004, 2019; Ebihara et al.,2019)

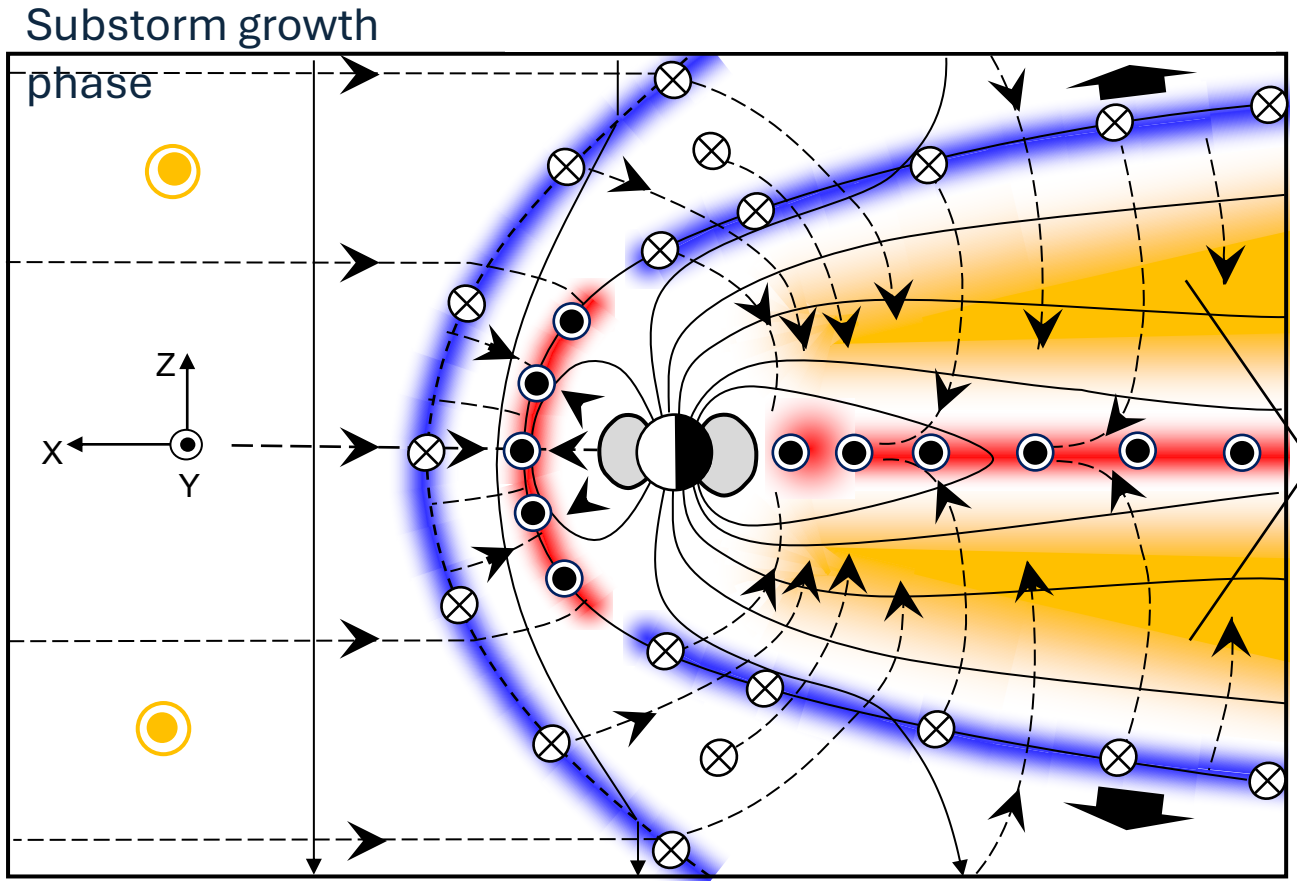


- Poynting flux S is smaller than kinetic energy flux by factor ~50
- Poynting flux is generated from kinetic energy of SW particles by regions of $\vec{J}.\vec{E} < 0$ in the shock, sheath and tail magnetopause
- Only about 10% of the energy entering the magnetosphere comes from Poynting flux in the undisturbed, upstream solar wind



Energy flow in the magnetosphere -substorm growth ($\partial W_B/\partial t > 0$)

(Cowley, 1991, Lockwood, 2004, 2019; Ebihara et al.,2019)

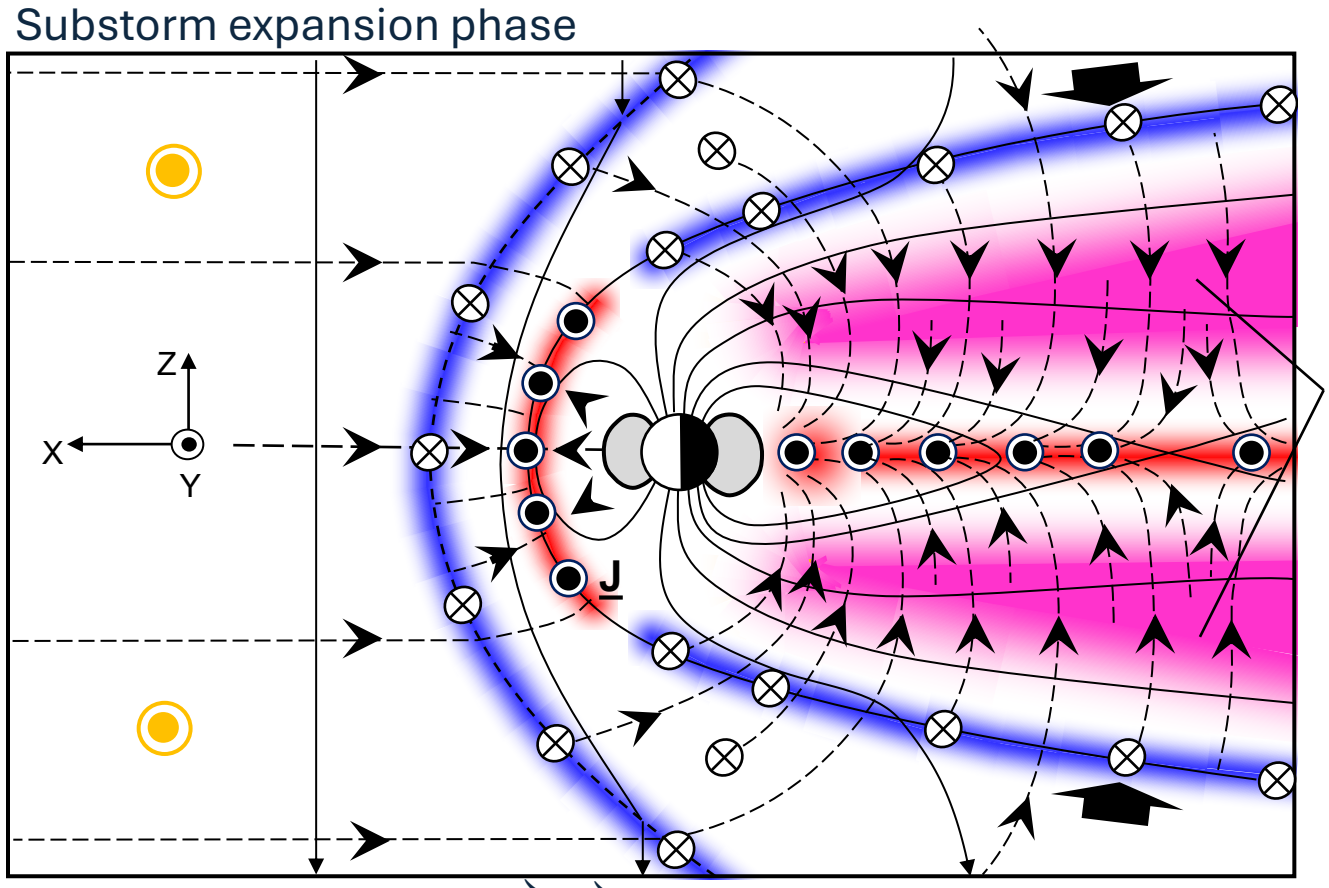


- Open flux accumulates in tail lobes where B and W_B rise



Energy flow in the magnetosphere -substorm expansion ($\partial W_B/\partial t < 0$)

(Lockwood, 2004, 2019; Ebihara et al.,2019)



- Open flux rapidly closed by reconnection in the cross-tail current sheet: lobe B and W_B fall

$dW_B/dt < 0$

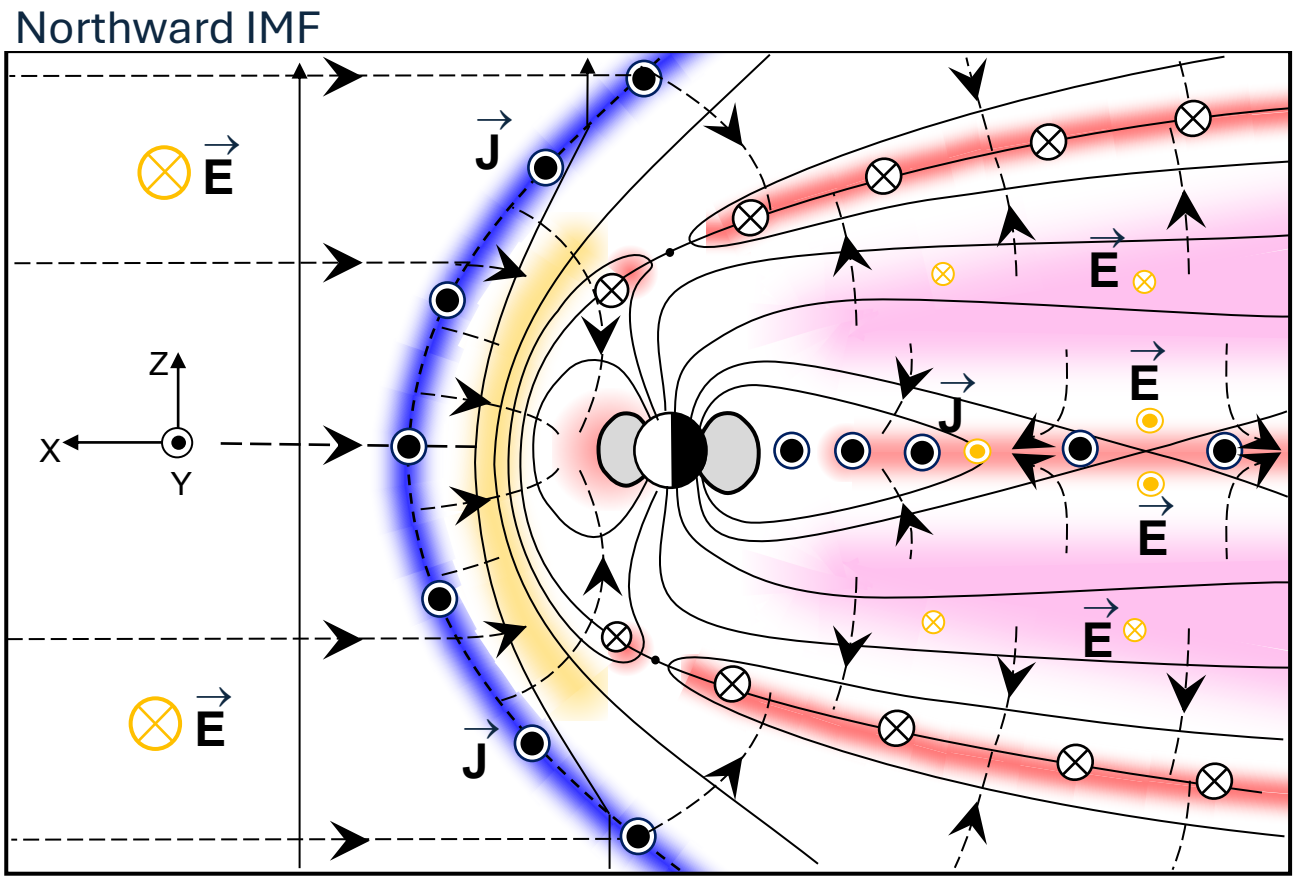
- Energy given to particles in the plasma sheet and ring current

- Also in ionosphere $\vec{J} \cdot \vec{E} > 0$ for Pedersen currents (by definition) which connect via Birkeland currents to the cross-tail current which means energy is also deposited in thermosphere



Energy flow in the magnetosphere -northward IMF ($\partial W_B/\partial t > 0$)

(Lockwood, 2004, 2019; Ebihara et al.,2019)



- This means that $B_Z > 0$ is **NOT** steady state but a slow decline in tail field and stored tail energy

- Both $\vec{E}$ and $\vec{J}$ in the bow shock are in the opposite direction to the $B_Z < 0$ case, so the bow shock still converts SW kinetic energy to Poynting flux
- Both $\vec{E}$ and $\vec{J}$ in the tail C.S. are in the same direction to the $B_Z < 0$ case, so the C.S. is still a sink of $\vec{S}$



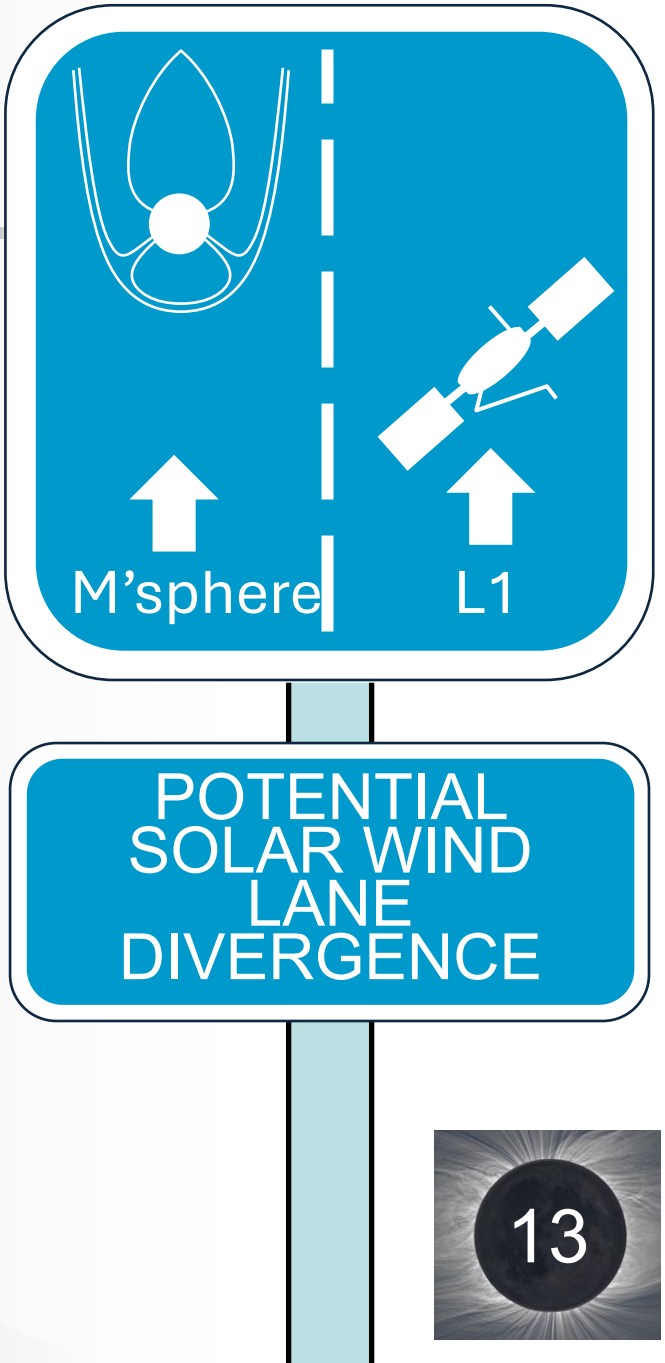
Pitfalls when using data from an L1 satellite





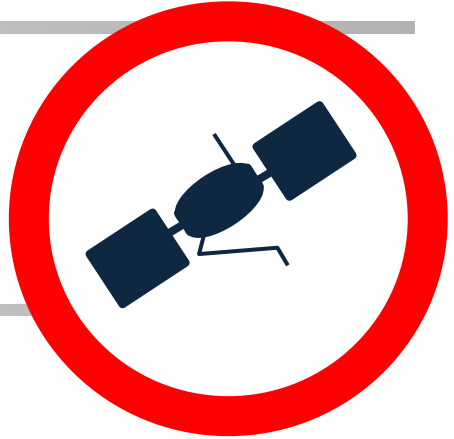
How good a predictor of near-Earth solar wind are data from an L1 halo orbit?

- **A**. Solar wind that passes over L1 satellite may miss Earth
- **B**. Solar wind may change during transit from L1 to Earth
- **C**. Estimated propagation time from satellite to Earth may be wrong
- We usually deal with **C** using a lag-correlogram (correlation coefficient as a function of lag) and the optimum lag is taken to give the peak correlation



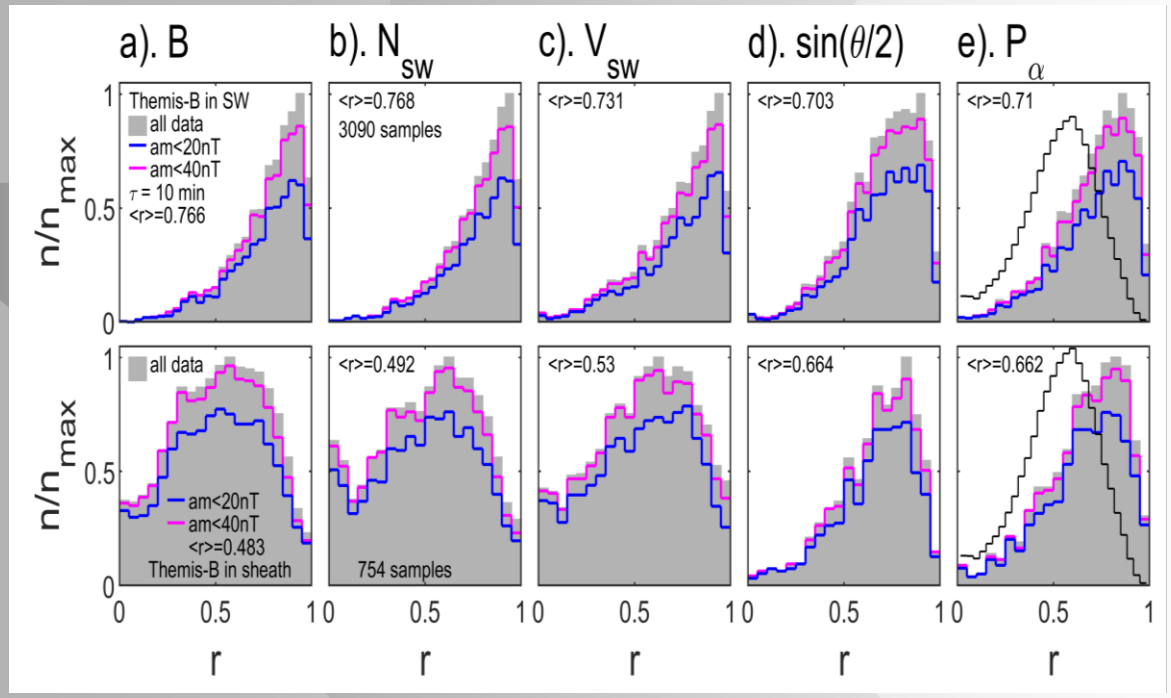


Correlations between data from L1 and Themis-B just outside magnetosphere



Distributions of peak correlations at optimum lag for 1-minute data

For 8-hour intervals from 2011-2018 (inclusive)



- 2011-2019 (inclusive)
- Top row: Themis-B is in near-Earth SW (3090 8-hr intervals)
- Bottom row: Themis-B is in magnetosheath (745 8-hr intervals
- P_α is a combination of SW parameters designed to predict SML index called a "coupling function"
- The black lines in (e) are the distribution of correlations of P_α and SML

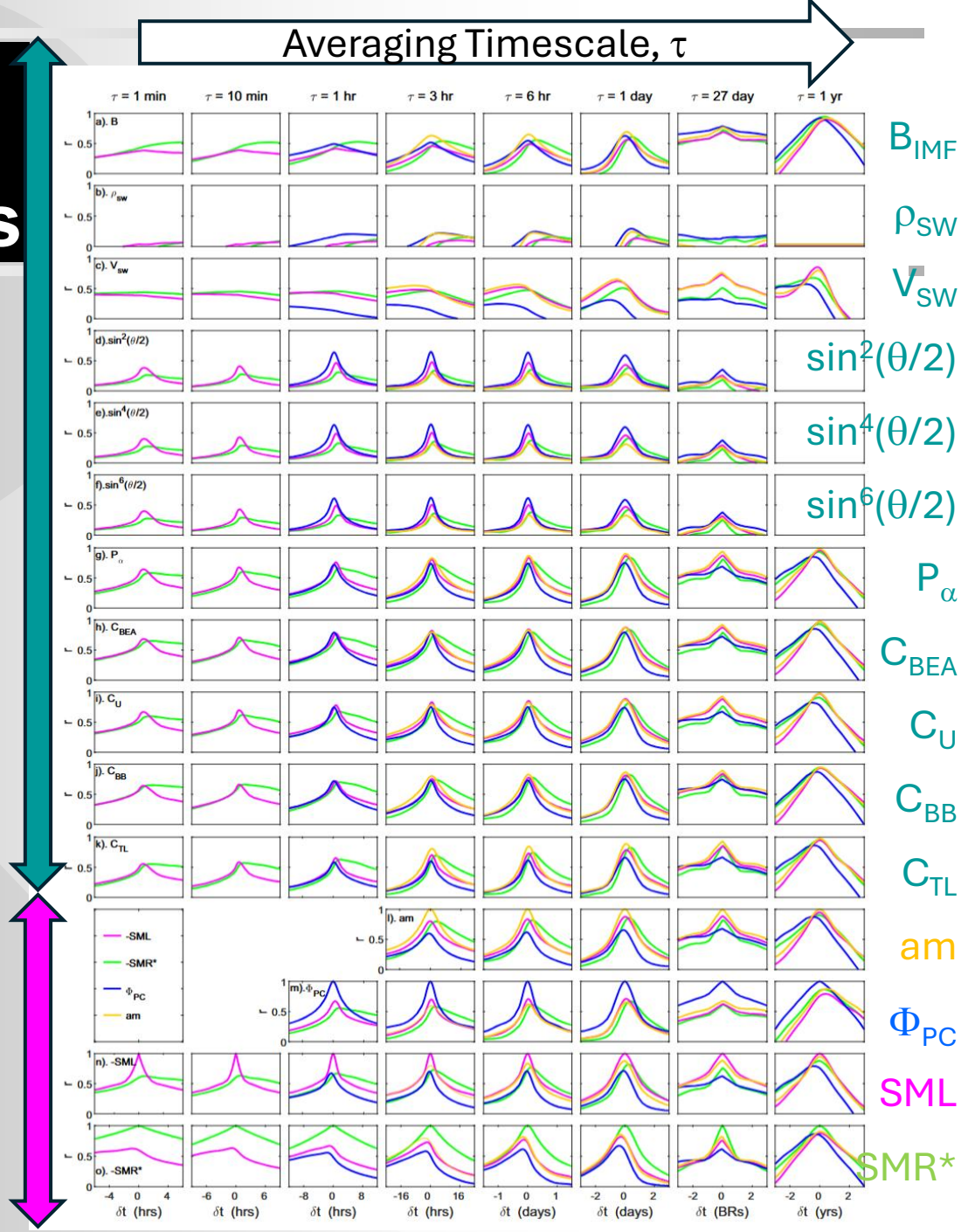
- Effects **A** and **B** in interplanetary space can clearly be seen
- Very little correlation in $sin(\theta/2)$ or P_α is lost in crossing the bow shock
- But a lot of correlation is lost between the magnetopause and the auroral oval



Lag Correlograms

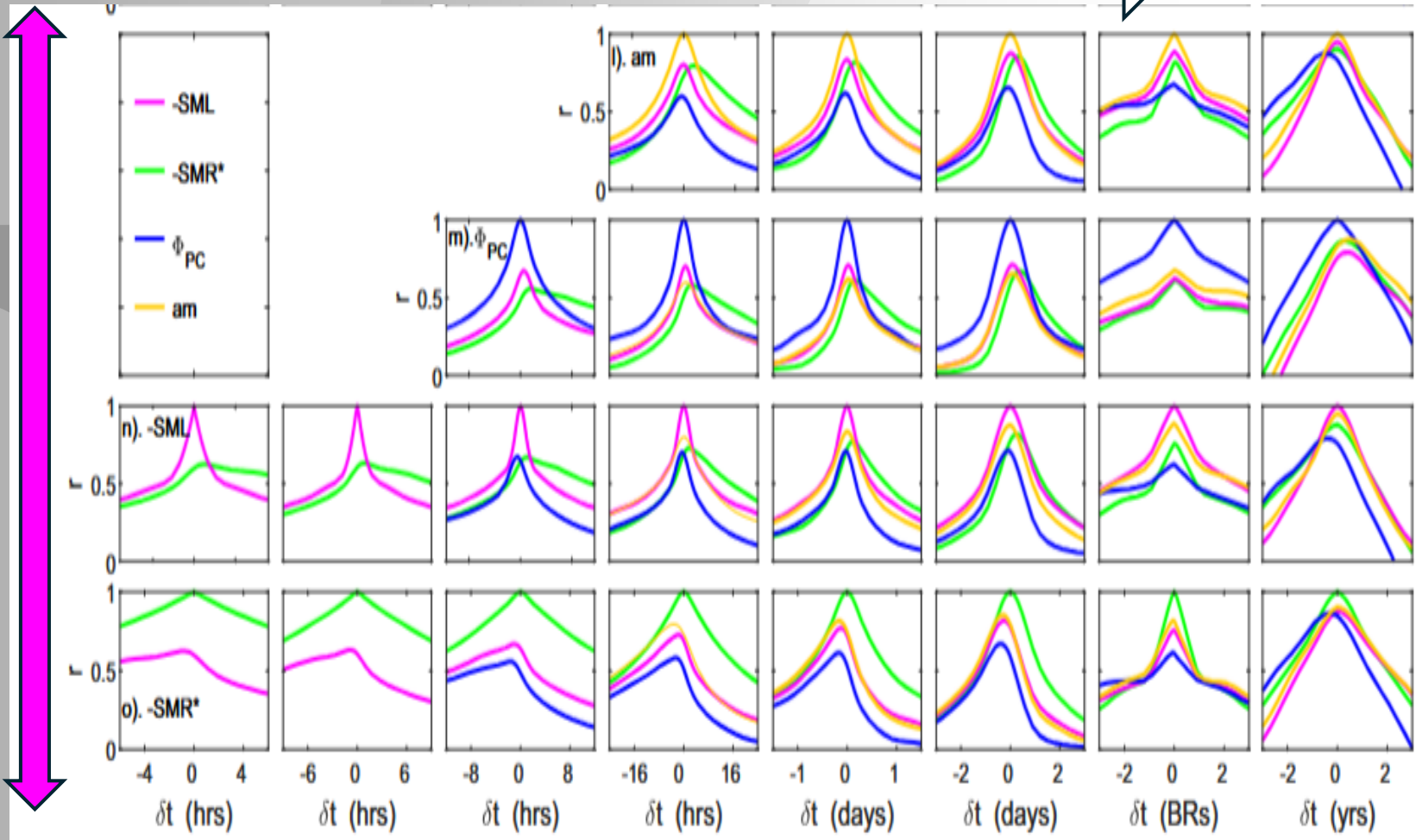
- Coupling function correlations with terrestrial disturbance indices that are high for long averaging periods do NOT work well on shorter times

- Correlations between terrestrial disturbance indices are only moderately high: so there is no such thing as a “Universal” coupling function and they need to be tailored to what is being predicted



Lag Correlograms

Averaging Timescale, τ



am

Φ_{PC}

SML

SMR*

1 min | 10 min | 1 hr | 3 hr | 1 day | 6 days | 27 days | 1 year

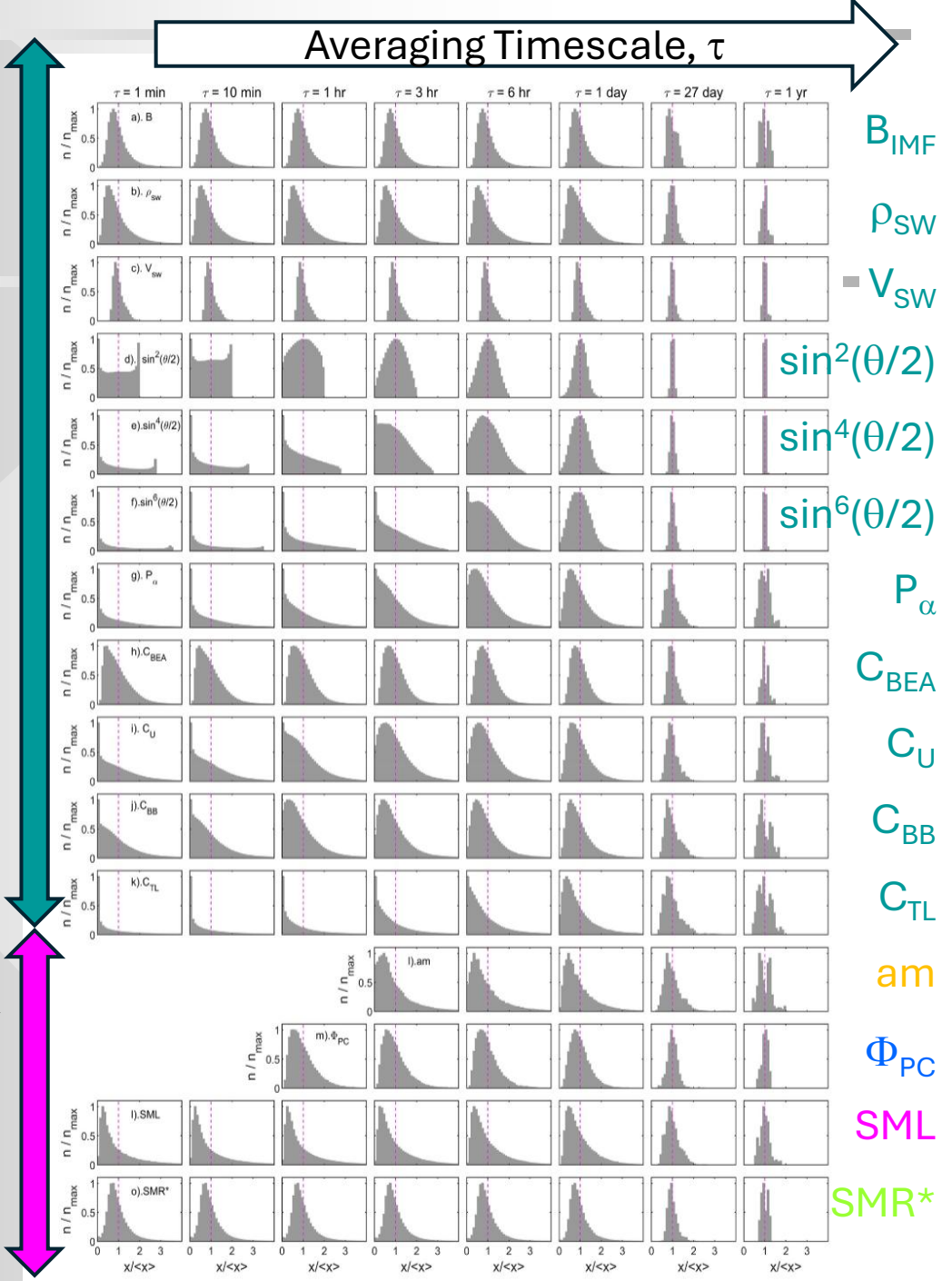
Distributions

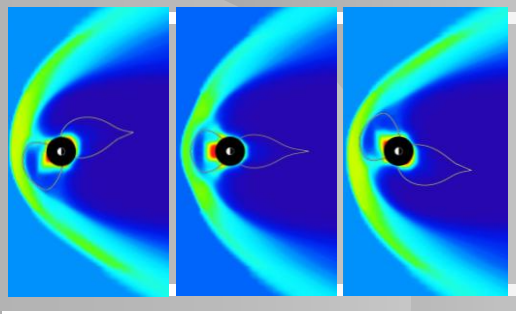
Central limit theorem means increasing τ collapses all distributions towards narrow Gaussians

- Coupling functions that work at high τ have unrealistic distributions at low τ

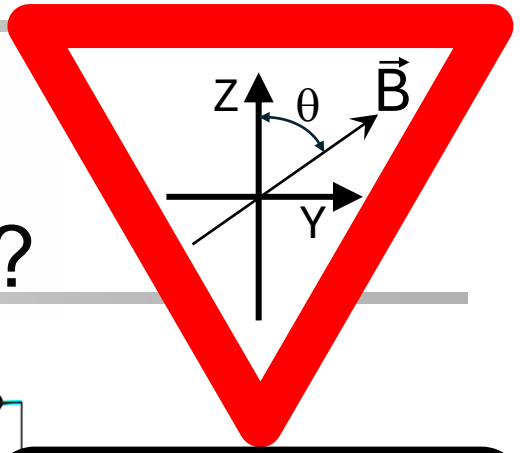
- Note IMF orientation factors $\sin^n(\theta/2)$ reduce to a constant value for $\tau \geq 1$ year

- other IMF parameters and - terrestrial indices have lognormal distributions

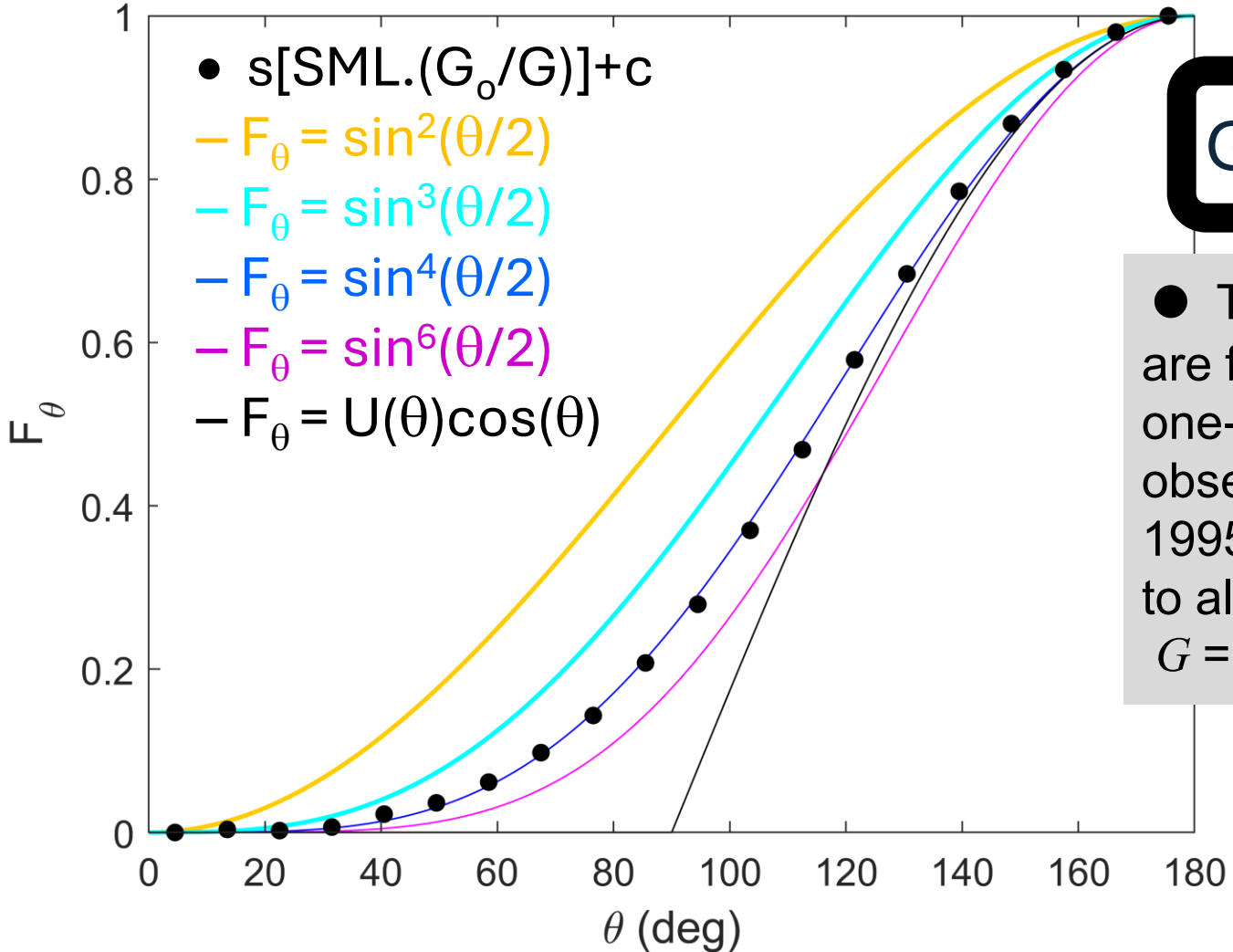




Why do IMF orientation factors behave so differently?

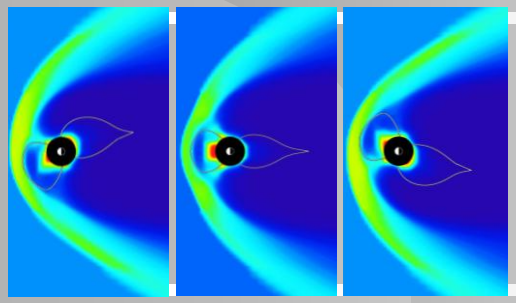


GSM FRAME



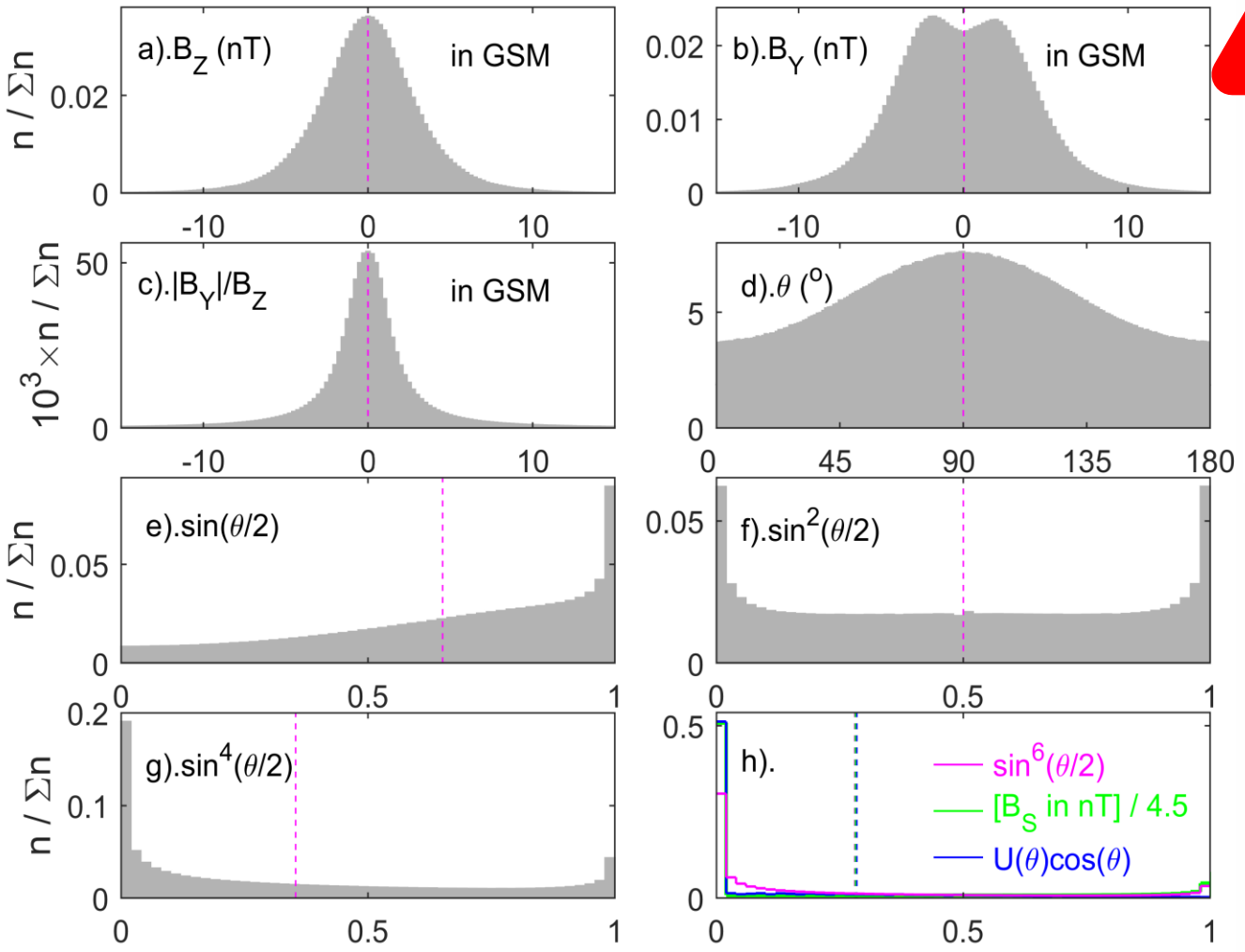
- The black points are from 11,646,678 one-minute SML observations from 1995-2020, corrected to allow for best fit

$$G = B_{\perp}{}^{a} \cdot \rho_{sw}{}^{b} \cdot V_{sw}{}^{c}$$

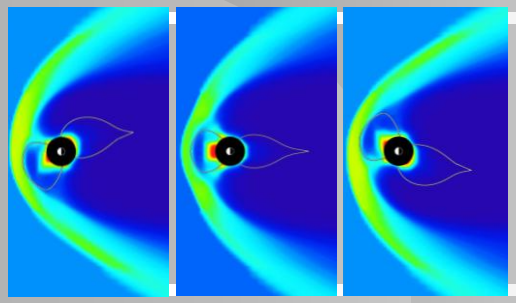


Averaging and weighting





- The origin of the weird observed distribution of $sin^{d}(\theta/2)$
- 11,646,678 one-minute data samples 1995-2020



Averaging and weighting: changes with averaging timescale

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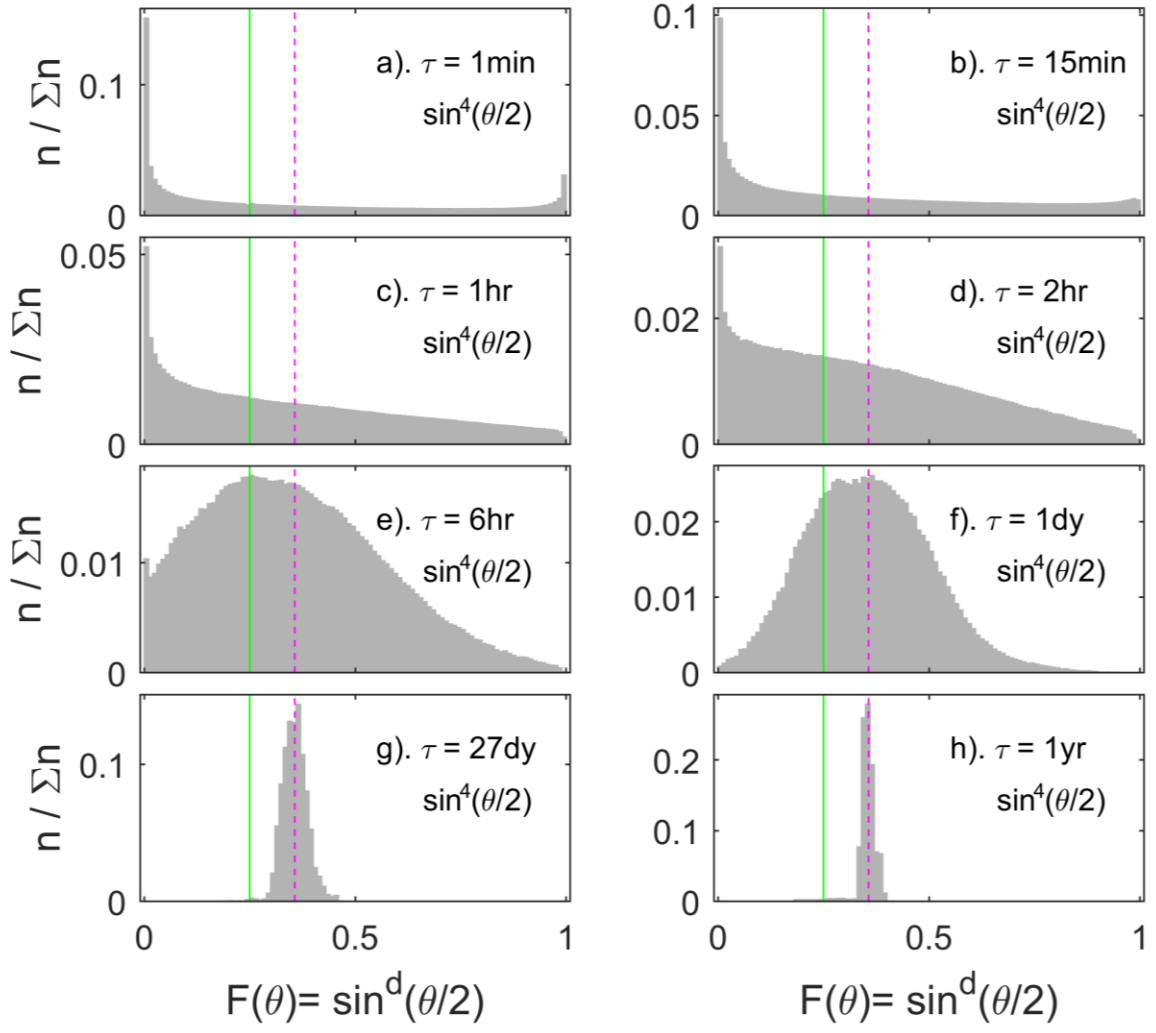


- The central limit theorem at work!
- This is for $sin^4(\theta/2)$
- Distribution evolves from weird, to less weird, to log-normal, to Gaussian, to delta function
- Explains why we do not need IMF orientation for annual means



The epsilon factor, $\varepsilon = B^2 V_{sw} \sin^4(\theta/2)$

(comparisons by Finch and Lockwood, 2007)

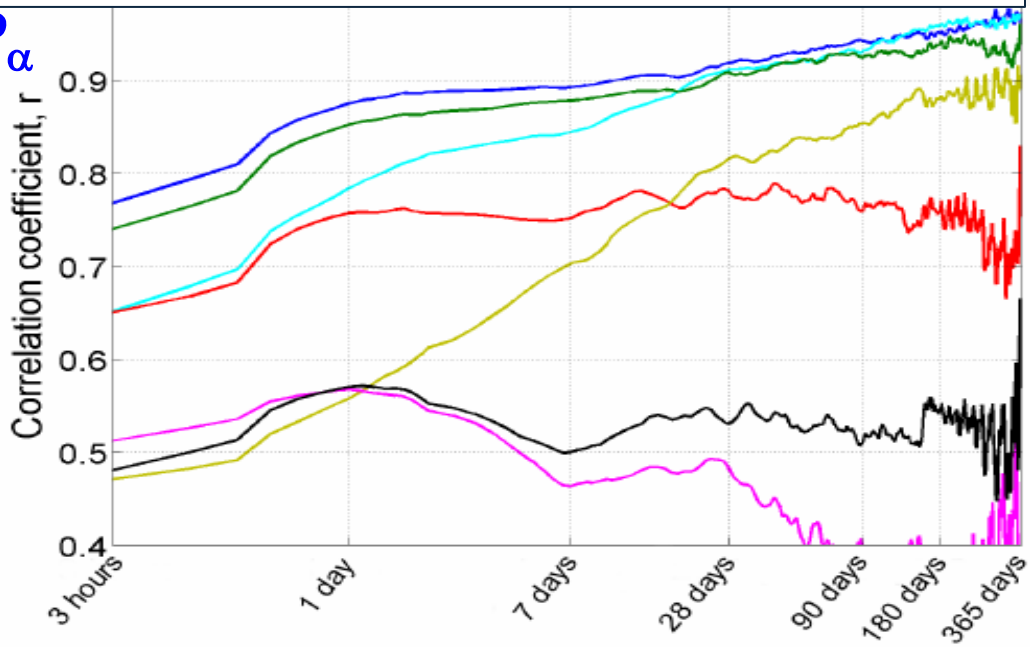


- Incorrect theoretical basis: assumes relevant solar wind power is Poynting flux: result ε performs less well at all τ

ε B V_{SW}^2 BV_{SW}^2 $B_s V_{SW}^2$

solar wind dynamic pressure, p_{SW}

Power input to the magnetosphere, P_α



Averaging timescale τ $\rightarrow$

- B = IMF, V_{sw} = solar wind speed, θ = IMF clock angle in GSM
- comparison allows for the effects of data gaps and of weightings given to datapoints by virtue of their frequency of occurrence
- correlations with *am* (best truly global index)
- Do not use ε ! (even to benchmark others as it is not a good test)



Simple theory-based coupling functions

1. Energy transfer into the magnetosphere

(Vasyluinas et al., 1982)

- Magnetospheric Power Input

$$P_\alpha = (\pi L_o^2) \times (m_{sw} N_{sw} V_{sw}^2/2) V_{sw} \times (t_r)$$

- from pressure balance & hemispheric dayside m'sphere:

$$L_o = cL_s = ck_1 (M_E^2/P_{sw}\mu_o)^{1/6}$$

- Vasyluinas et al. (1982) dimensionless transfer function:

$$t_r = k_2 M_A^{-2\alpha} \sin^d(\theta/2)$$

- Alfvén Mach #, $M_A = V_{sw}(\mu_o m_{sw} N_{sw})^{1/2}/B_{sw}$ • α is the "coupling exponent" (the one free fit parameter) • L_s is stand-off distance of nose and $c = L_o/L_s$ the magnetopause shape factor • M_E is the Earth's magnetic moment • N_{sw} is the solar wind concentration • V_{sw} is the solar wind velocity, • B_{sw} is the IMF magnitude • θ is the clock angle that the IMF makes with the north in the Earth's GSM frame of reference. • k_1 is the "blunt nose" sheath flow factor • k_2 is a constant • d is the IMF orientation factor exponent



Simple theory-based coupling functions

(Vasyluinas et al., 1982)

- Gives magnetospheric Power Input

$$P_\alpha = \{M_E^{2/3} c^2 k_1 k_2 \pi / (2\mu_o^{(1/3-\alpha)})\} \times B_\perp^{2\alpha}\ \rho_{sw}^{(2/3-\alpha)}\ V_{sw}^{(7/3-2\alpha)}\ sin^{d}(\theta/2)$$

- Use IGRF model to get M_E
- c taken to be a constant (OK for solar SW pressure changes but not so good for IMF B_z changes because of dayside erosion/tail flaring)
- $\{M_E^{2/3} c^2 k_1 k_2 \pi/(2\mu_o^{(1/3-\alpha)})\}$ can usually be taken to be a constant: I often use P_α/P_o where $P_o = <P_\alpha>_{\text{all data}}$, so this term cancels out
- Vasyluinas et al. point out that d is not and independent fit parameter but is set for a given α to ensure linearity with response
- Vasyluinas et al. find transverse component of $B_\perp = (B_z^2 + B_y^2)^{1/2}$ actually works better than B
- Derive the 1 **ONE** fit parameter, α, to maximise correlation of P_α with the terrestrial disturbance index to be predicted



Simple theory-based coupling functions

2. Applied voltage

(Reiff and Luhmann, 1986; Siscoe et al, 2002; Lockwood and McWilliams, 2021)

- Relevant solar wind electric field

$$E_{sw} = B_{\perp} V_{sw} \sin^{d}(\theta/2)$$

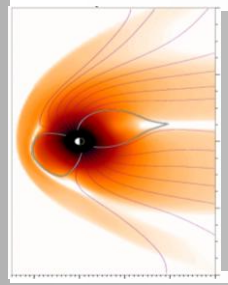
- Voltage across the diameter of the magnetosphere

$$\Phi_M = 2L_o B_{\perp} V_{sw} sin^{d}(\theta/2) = ck_3 (M_E^2/P_{sw}\mu_o)^{1/6} B_{\perp} V_{sw} sin^{d}(\theta/2)$$

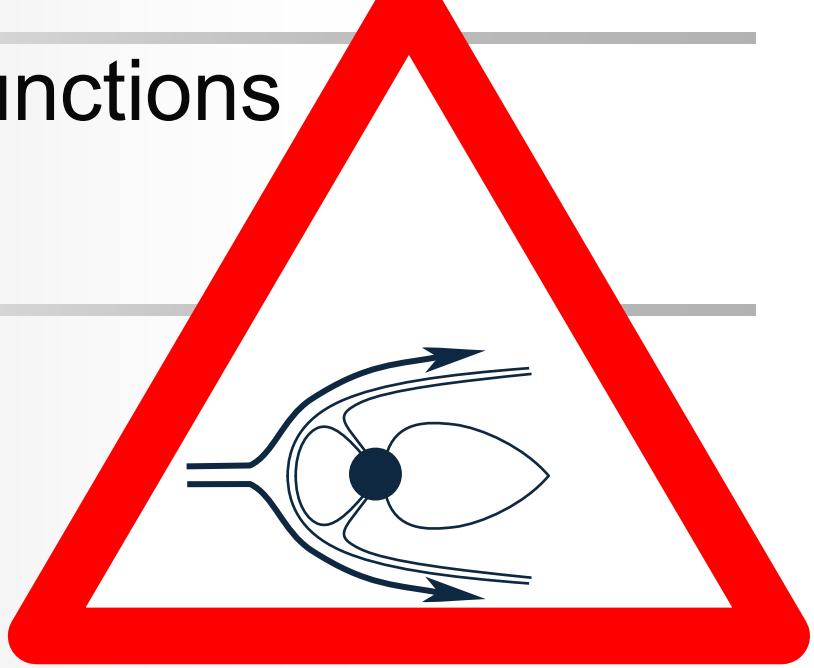
- Polar cap voltage for reconnection efficiency η :

$$\Phi'_{PC} = \eta \Phi_M = \eta k_4 B_{\perp} \rho_{sw}^{-1/6} V_{sw}^{2/3} sin^{d}(\theta/2)$$

- BUT η is not a constant *(e.g. Borovsky and Birn, 2014)*
- any dependence of η on $B_{\perp}$, ρ_{sw} or V_{sw} would change the exponents in the predicted Φ_{PC}



Empirical coupling functions

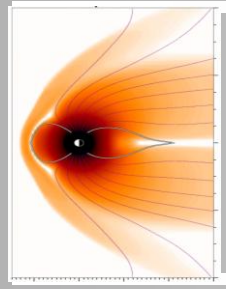


- There are many more complex theoretical functions
- A common empirical form also encompassing 1st-order theories is:

$$C_f = B_\perp{}^a \rho_{sw}{}^b V_{sw}{}^c \sin^d(\theta/2)$$

- Where the exponents a, b and c are fit parameters (c.f. for P_α with $\alpha = 1/3$: $a = 0.67$, $b = 0.33$ and $c = 1.67$ for Φ'_{PC} with constant η: $a = 1$, $b = -0.17$ and $c = 0.67$)

- In fact, to ensure linearity we cannot consider d to be a 4th independent fit parameter



A Pitfall

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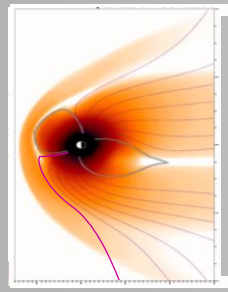
- with too many free fit parameters we can start to fit to the noise in the training data - resulting in the fit having reduced predictive power

- recognised pitfall when signal-to-noise ratio is low in (e.g.) climate science and population growth but was often not recognised in space physics, especially before systems research and machine leaning were introduced into the field



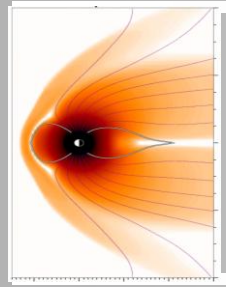
- How to avoid it? In “k-fold” cross-validation, partition the data into k subsets (“folds”). Then, iteratively train the algorithm on all but one fold and use that as the test set (the “holdout fold”)



Sources of noise



- observation errors in interplanetary measurements
- observation errors in terrestrial disturbance index or indicator
- propagation errors: lag variations and spatial structure in interplanetary space
- data gaps
- effects of averaging & timescale
- non-linear response, pre-conditioning, time history
- dipole tilt effects (on ionospheric conductivities, magnetospheric structure and current sheets, and magnetopause coupling)



Effects of the persistence of interplanetary parameters

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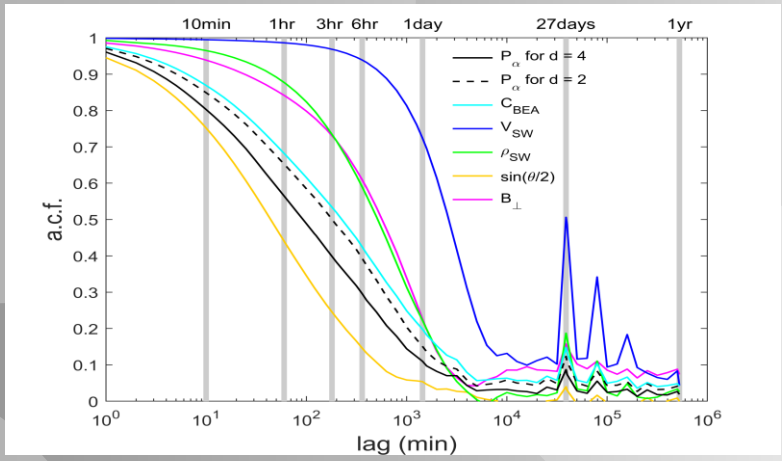
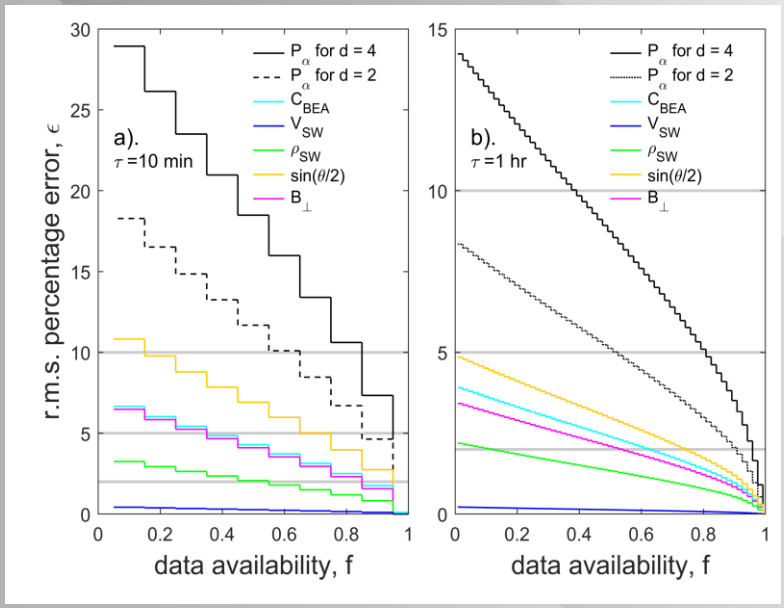
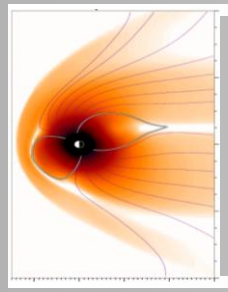
Lockwood et al. (2019), Lockwood (2022)





- 10,306,769 1-min samples for 1996-2020 (inclusive; an interval when data gaps are relatively rare and short)
- acfs V_{SW} has highest persistence, means we only need one sample in 10 min or even an hour for mean value to get rms error below 2%
- But for IMF orientation's low persistence (high variability) means we need all samples in 10 min and 75% of samples in an hour to get rms error < 2%
- 5,153,517 10-minute samples for which all 10 1-min samples available
- 58,923 1-hour samples for which all 60 1-min samples available
- Remove (1-f) samples at random and estimate error ξ by comparing with known value for f = 1. Repeated 10 times for each hourly/10-min mean

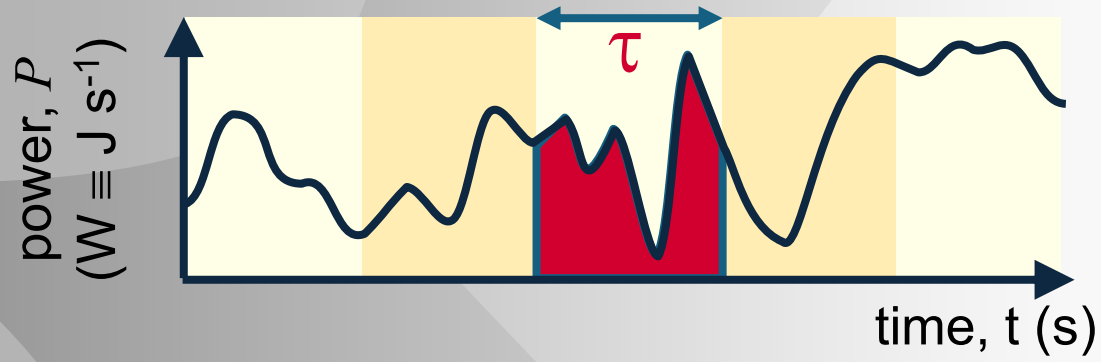




Timescale & averaging



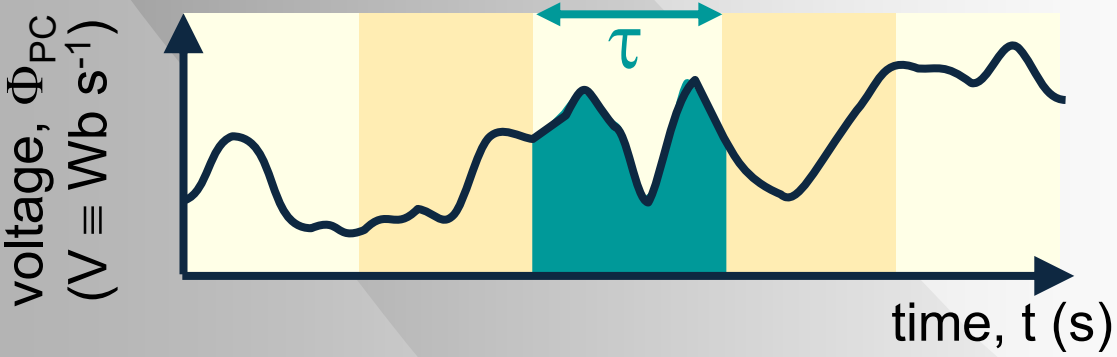
- Consider energy input into the magnetosphere



- We want the total energy input in the averaging time τ

$$E_\tau = \int_\tau P\,dt = \tau \langle P \rangle_\tau$$

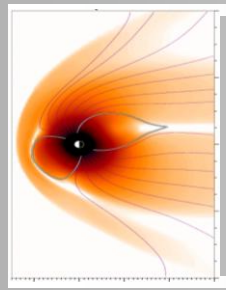
- Likewise reconnection voltage (flux transfer rate)



- We want the total flux reconnected in the averaging time τ

$$F_\tau = \int_\tau \Phi_P\,dt = \tau \langle \Phi_P \rangle_\tau$$

- So for coupling function C_f we want $\int_\tau C_f\,dt = \tau \langle C_f \rangle_\tau$

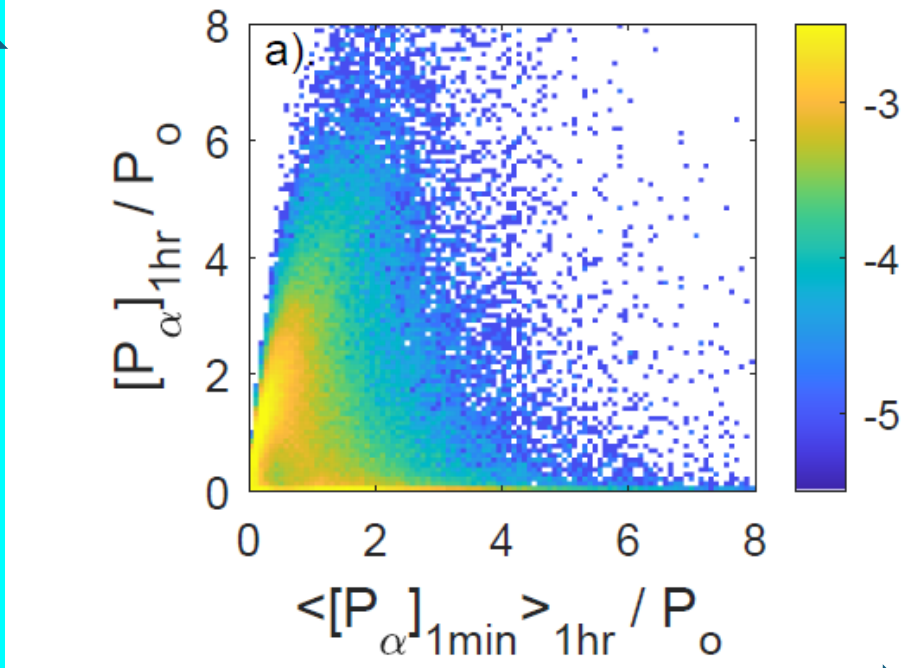


Timescale, averaging and weighting



- We want $\int_\tau C_f\, dt = \tau < C_f >_\tau$
- So we want $< C_f >_\tau = < B_\perp{}^a\, \rho_{sw}{}^b\, V_{sw}{}^c\, sin^d(\theta/2) >_\tau$
- some studies use $[C_f] = <B_\perp>^a <\rho_{sw}>^b <V_{sw}>^c sin^d(\theta_{1hr}/2)$

What we often use



What we really want

- where $\tan(\theta_{1hr}) = (|<B_y>_{1hr}| / <B_z>_{1hr})$
- this is for example of P_α for α = 1/3, giving a = 2/3, b = 1/3 and c = 5/3 with d = 4
- r = 0.28!!!!



Determination of optimum d for (e.g.) predicting am

(Vasyluinas et al., 1982)

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- Break out the IMF orientation factor $F(\theta)$ from the coupling function, C_f by defining G such that

$$G = C_f / F(\theta)$$

So for our general form $G = B_\perp^{\,a}\ \rho_{sw}^{\,b}\ V_{sw}^{\,c}$ and $F(\theta) = sin^{d}(\theta/2)$

- we need C_f to be a linear predictor with index (e.g. am)

$$am = s_{am}\, C_f + i_{am} \quad = \quad s_{am} G\, F(\theta) + i_{am}$$

- Which yields

$$F(\theta) = (1/s_{am}) \times (am - i_{am}) / G \ = \ \text{“}\ R_{am}\ \text{”}$$

So if we bin the data by $F(\theta)$ and plot $\langle F(\theta) \rangle$ against $\langle R_{am} \rangle$ we get proportionality if our $F(\theta)$ is correct

R_{am} and G are set by a, b and c and so therefore are $F(\theta)$ and d – i.e., d is not a free fit parameter



Determination of optimum d for am data

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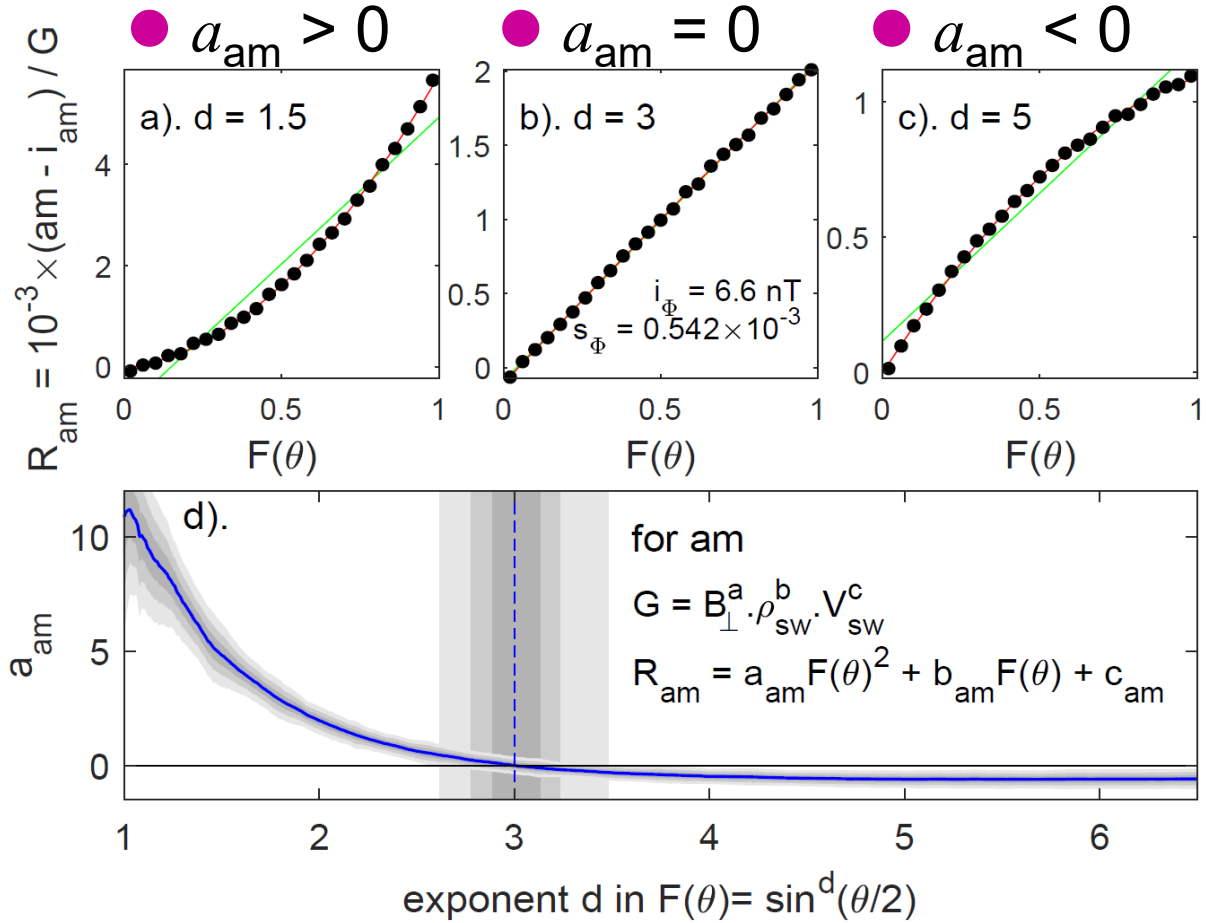


- To make C_f proportional to am, R_{am} needs to vary linearly with $F(\theta)$
- Sets d needed as where the quadratic term of fit polynomial, a_{am} falls to zero with 1-σ, 2-σ and 3-σ uncertainties

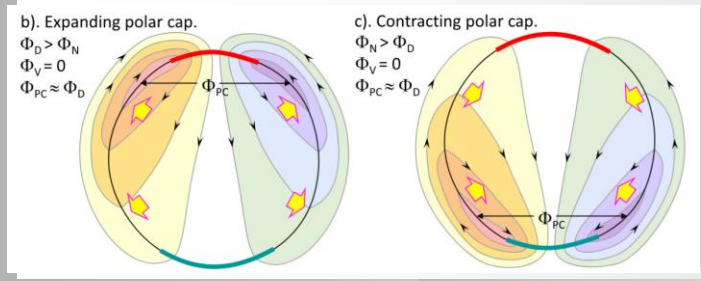
- a, b & c for each d found by a Nelder-Mead simplex search to minimize r.m.s. fit deviation of C_f to $am \rightarrow G$



Some key rules



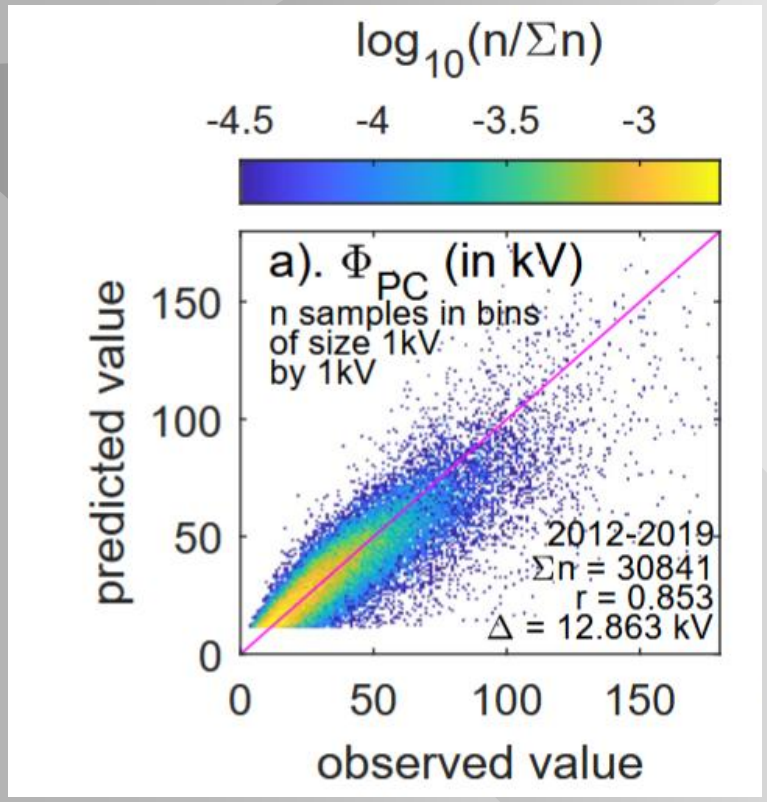
- Combine hi-res parameters into a coupling function and then average **DO NOT** average then combine
- Tailor your coupling function to what you are predicting
- **NEVER** interpolate data into data gaps: best approach is to find optimum lag and then piecewise mask out the corresponding data (allowing for the lag) in the other data series
- **ALWAYS** do a multi-fold fit to avoid overfitting: at the very least use half data to generate the fit and half to test it
- Aim to make your coupling function a LINEAR predictor of what you are predicting. Distributions and averaging give statistical biases to certain clock angles, so IMF orientation factor must be determined by the linearity condition, not correlation



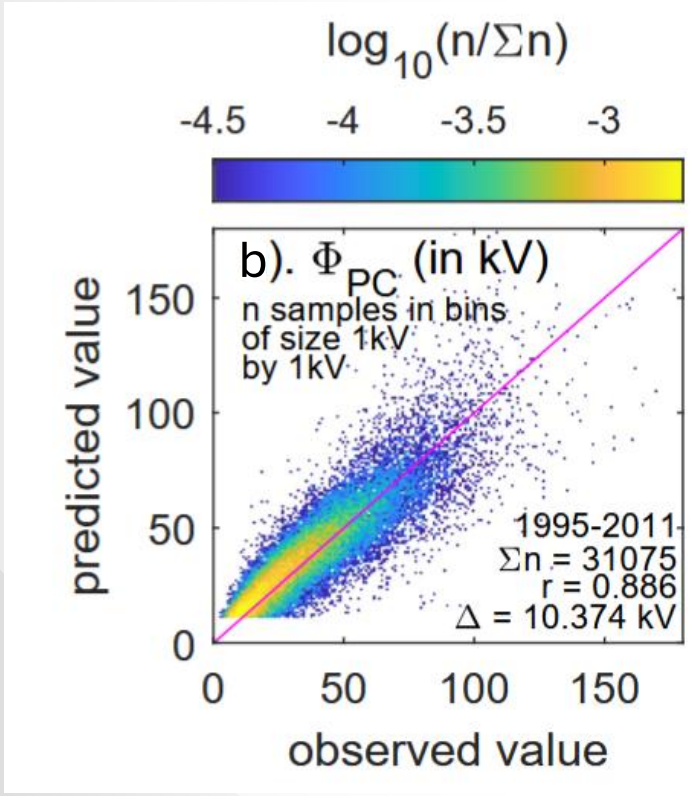
e.g. Prediction of Transpolar Voltage, Φ_{PC}

- predicted values $<C_f>_{1hr}$ and $<\Phi_{PC}>_{1hr}$ observations at optimum lag of 18.5 ± 1.3 min.

- Training data 2012-2019

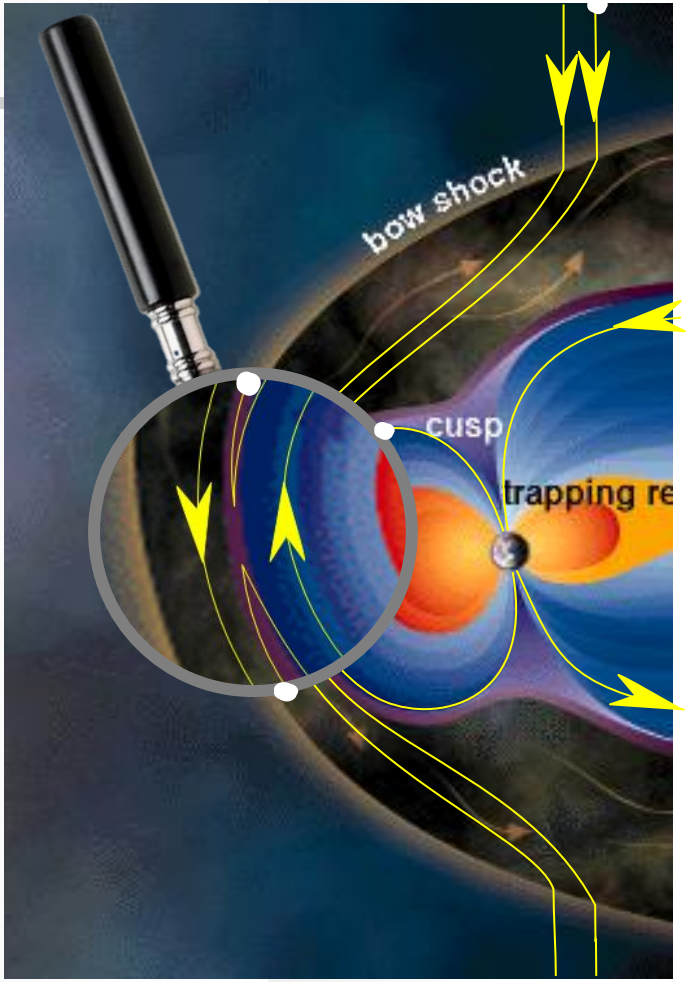


- Test data 1995-2011

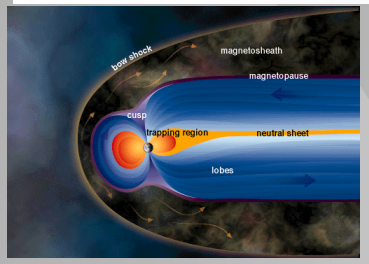




Further remarks



- The coupling function needs to be tailored to which magnetospheric state index you are using
- Even high-correlation coupling functions do not perform equally well over all parameter space
- preconditioning of the magnetosphere is an major issue which systems analysis techniques may well help with
- need to follow best practice (e.g. combine-then-average, avoid overfitting and ensure linearity) to avoid repeating mistakes that have been made in the past



The Russell-McPherron Effect

Russell & McPherron (1973) *doi: 10.1029/JA078i001p00092*

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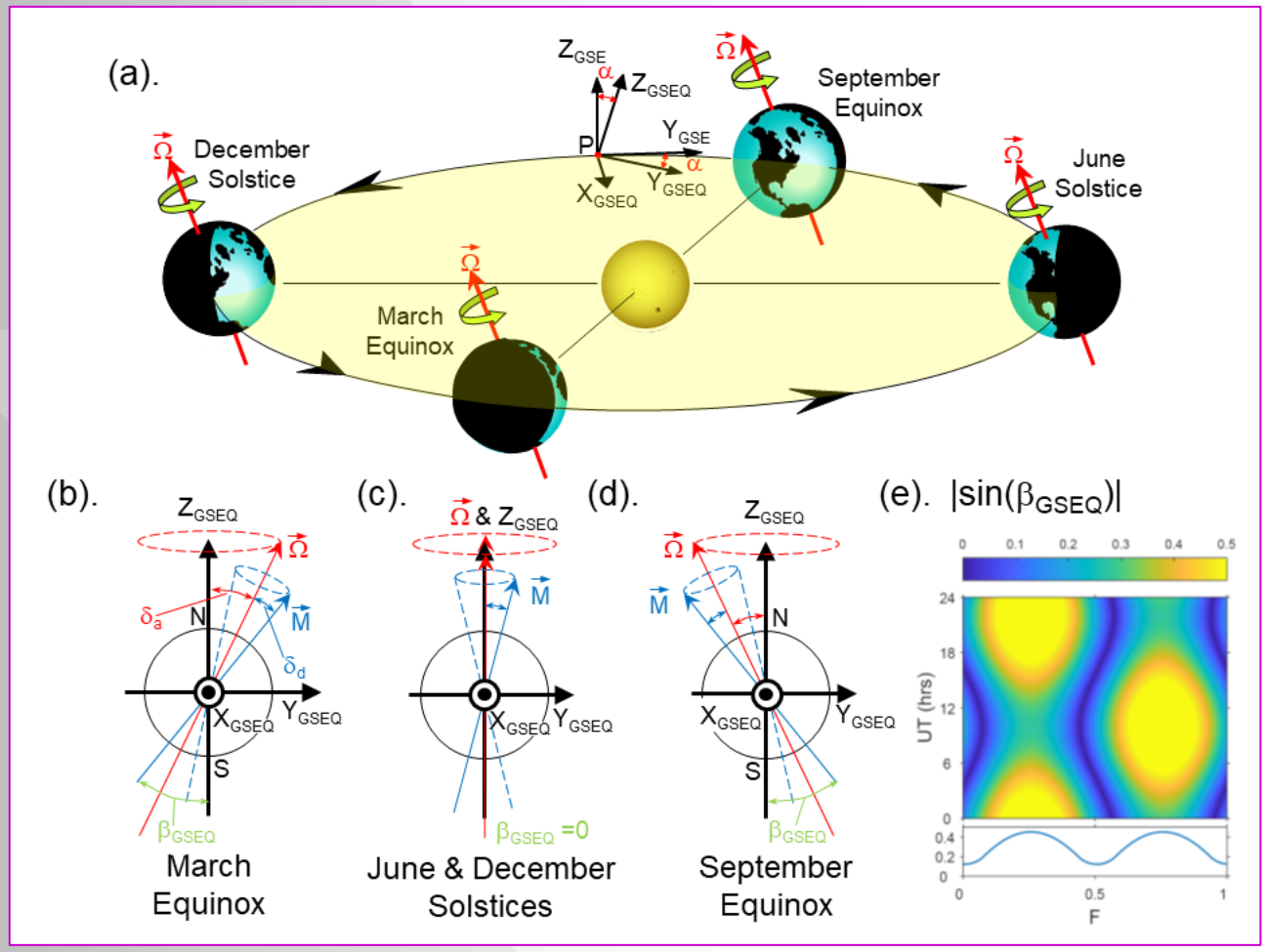
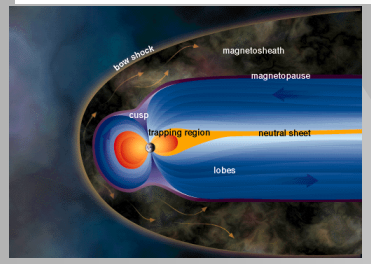
- The average IMF orientation in GSEQ has $[B_Z]_{GSEQ} = 0$
- Solar wind-magnetosphere coupling depends on $[B_Z]_{GSM}$ (< 0)
- GSM orientation depends on geomagnetic axis, $\vec{M}$



From: *Lockwood et al. (2020a), Semi-annual, annual and Universal Time variations in the magnetosphere and in geomagnetic activity: 1. Geomagnetic data, doi: 10.1051/swsc/2020023*



The Dcx Index

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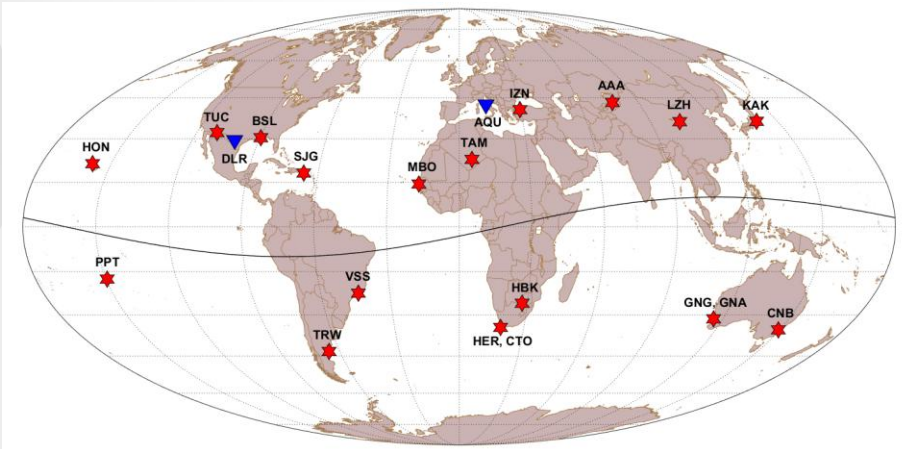
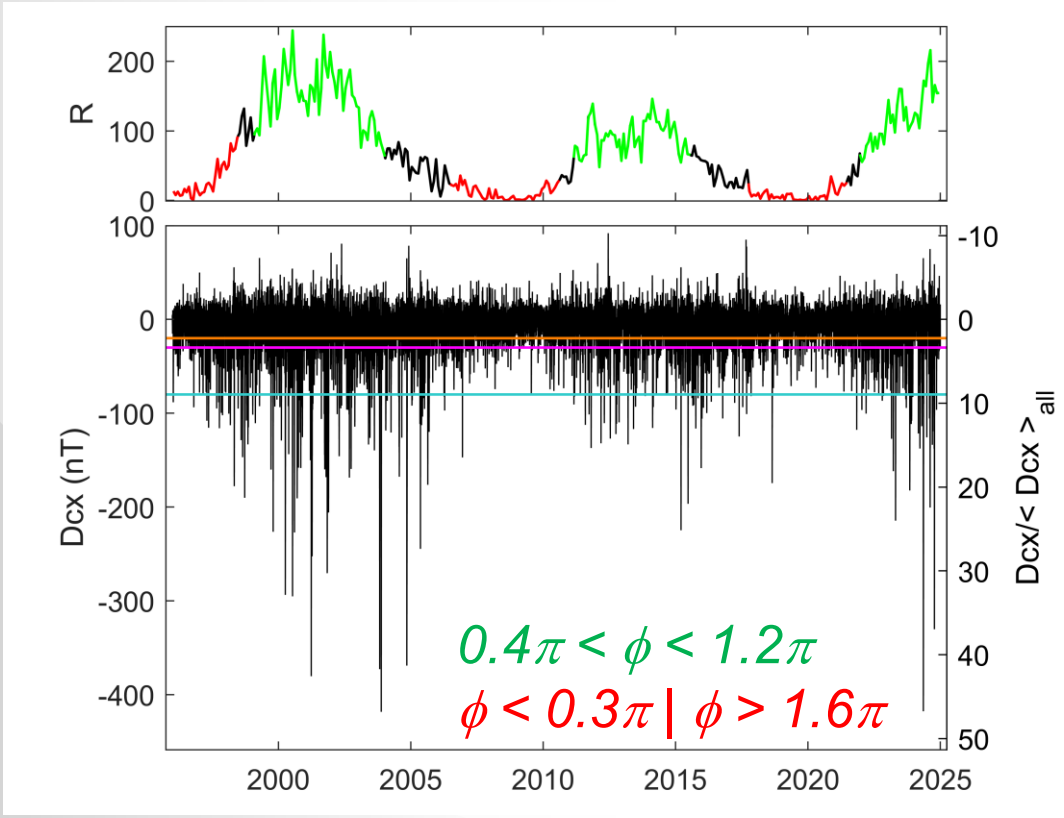
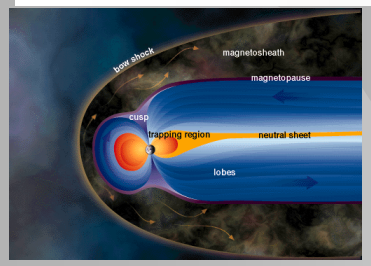
Karinen & Mursula (2005) doi: 10.5194/angeo-23-475-2005
Mursula & Karinen (2005) doi: 10.1029/2005gl023132

- Uses 15 stations which reduces excessive semi-annual variation of Dst

- Solar maximum and minimum here defined by the phase of the solar cycle, ϕ







Like Dst, Dcx shows an "axial" F-UT pattern

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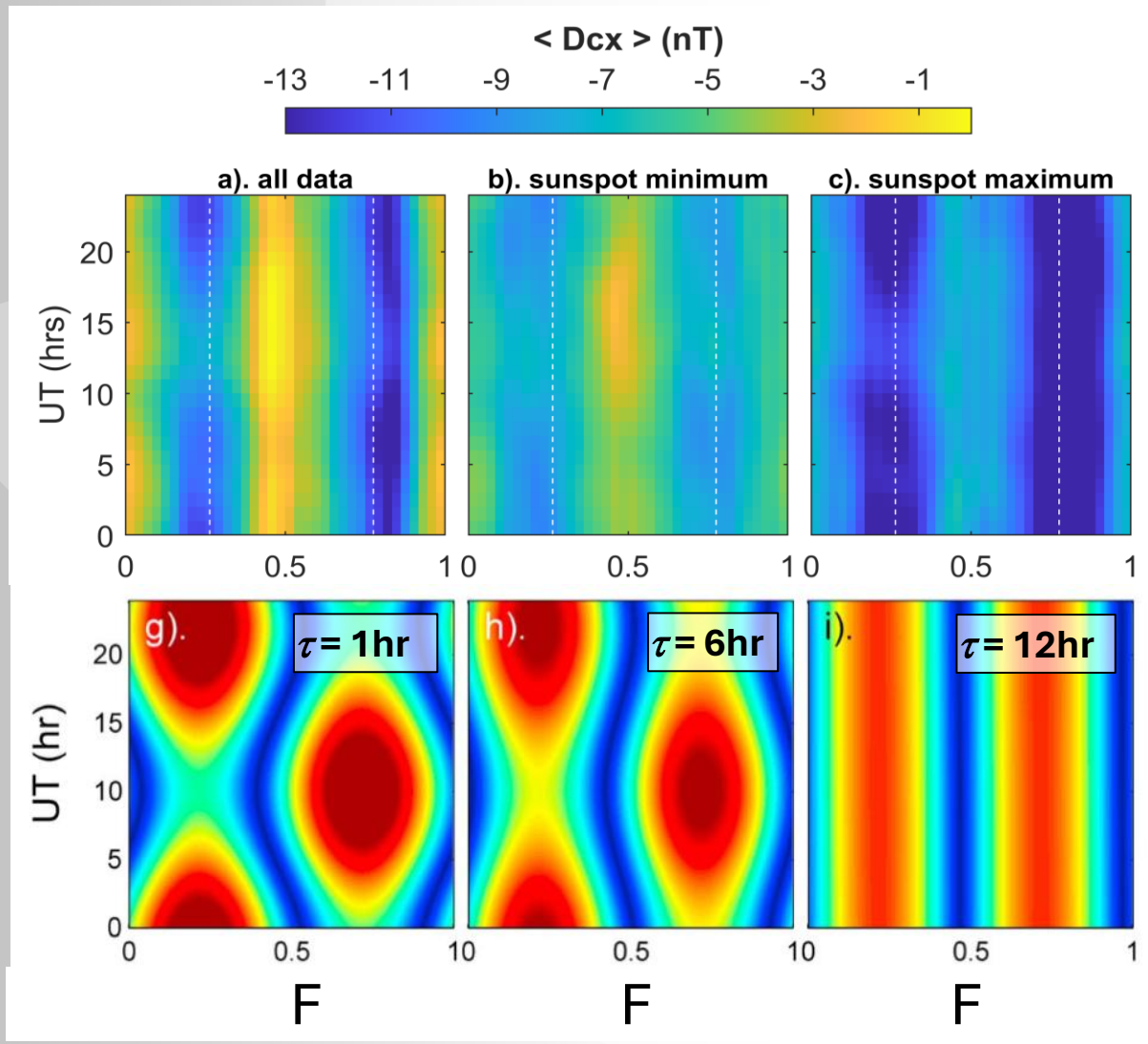
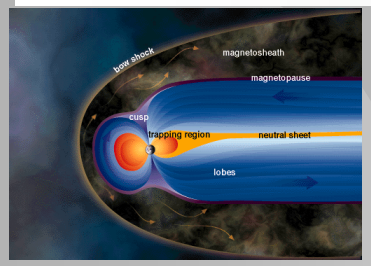
Lockwood et al (2016) doi: 10.1002/2016SW001375

- Not caused by an "axial" effect
- Time constant of response τ > 12 hrs averages out UT variation & turns an R-M pattern into an "axial" one





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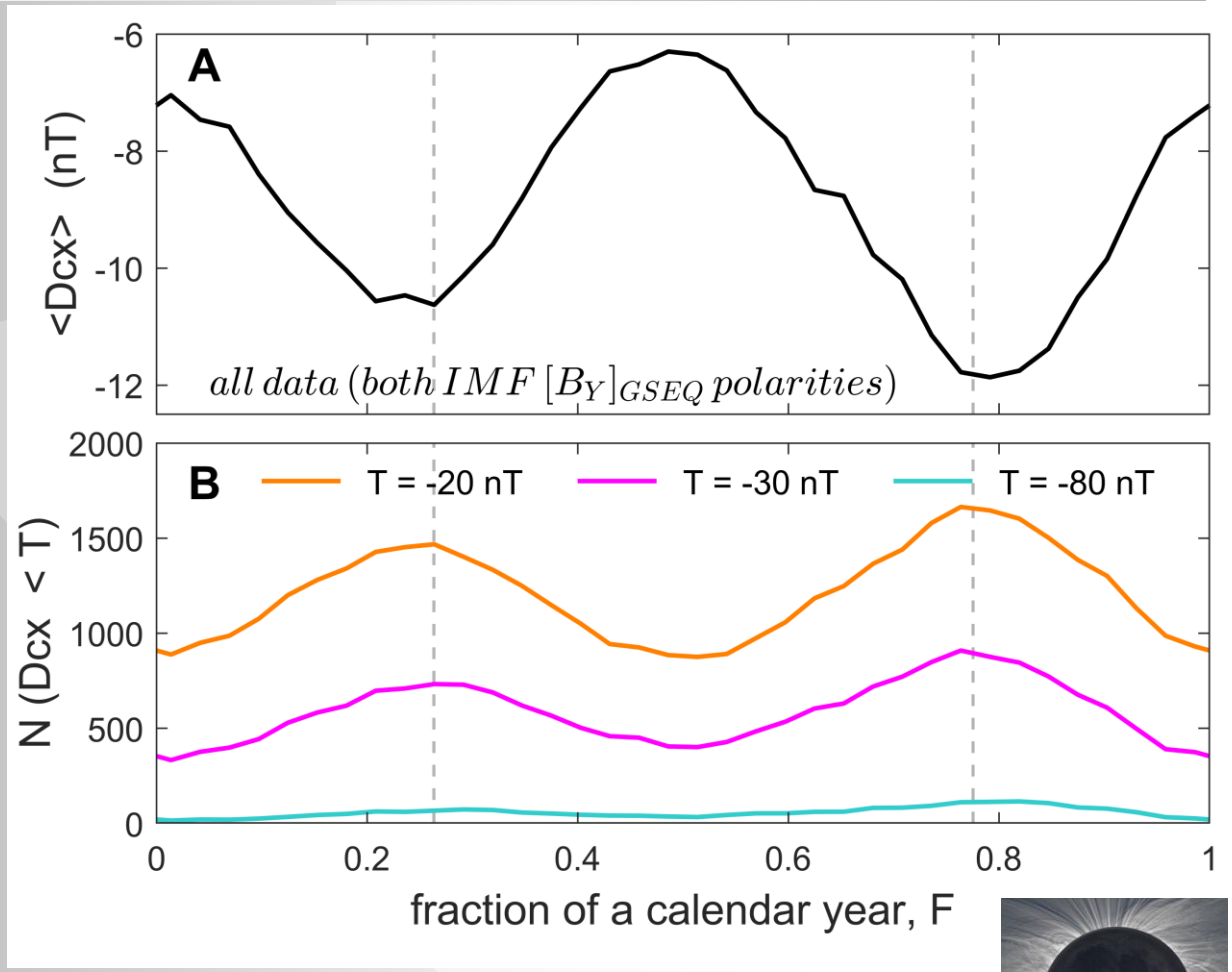
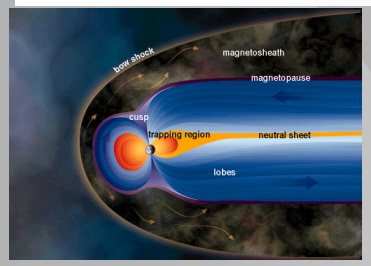
Semi-annual variation in Dcx

- Clear semi-annual variation with enhanced activity at the equinoxes
- Seen in occurrence of events exceeding disturbance thresholds
- Small effect for larger storms





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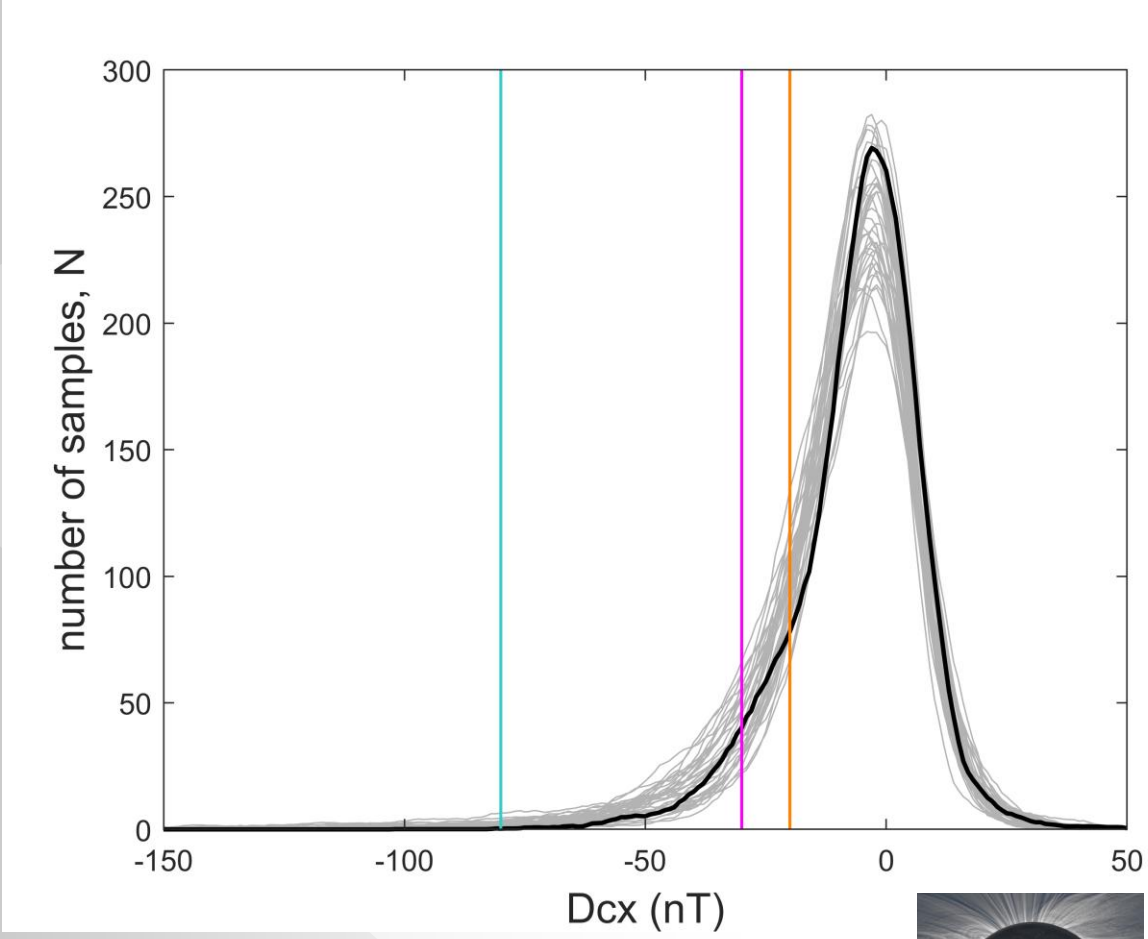
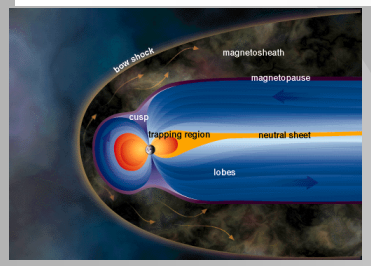
Distributions of hourly Dcx

(data for 1996-2024, inclusive)

- Gray lines: distributions for 36 bins of fraction of a calendar year, F
- Black line: distribution of all hourly Dcx values
- For each F bin take distribution of ΔDcx, the deviation from the mean





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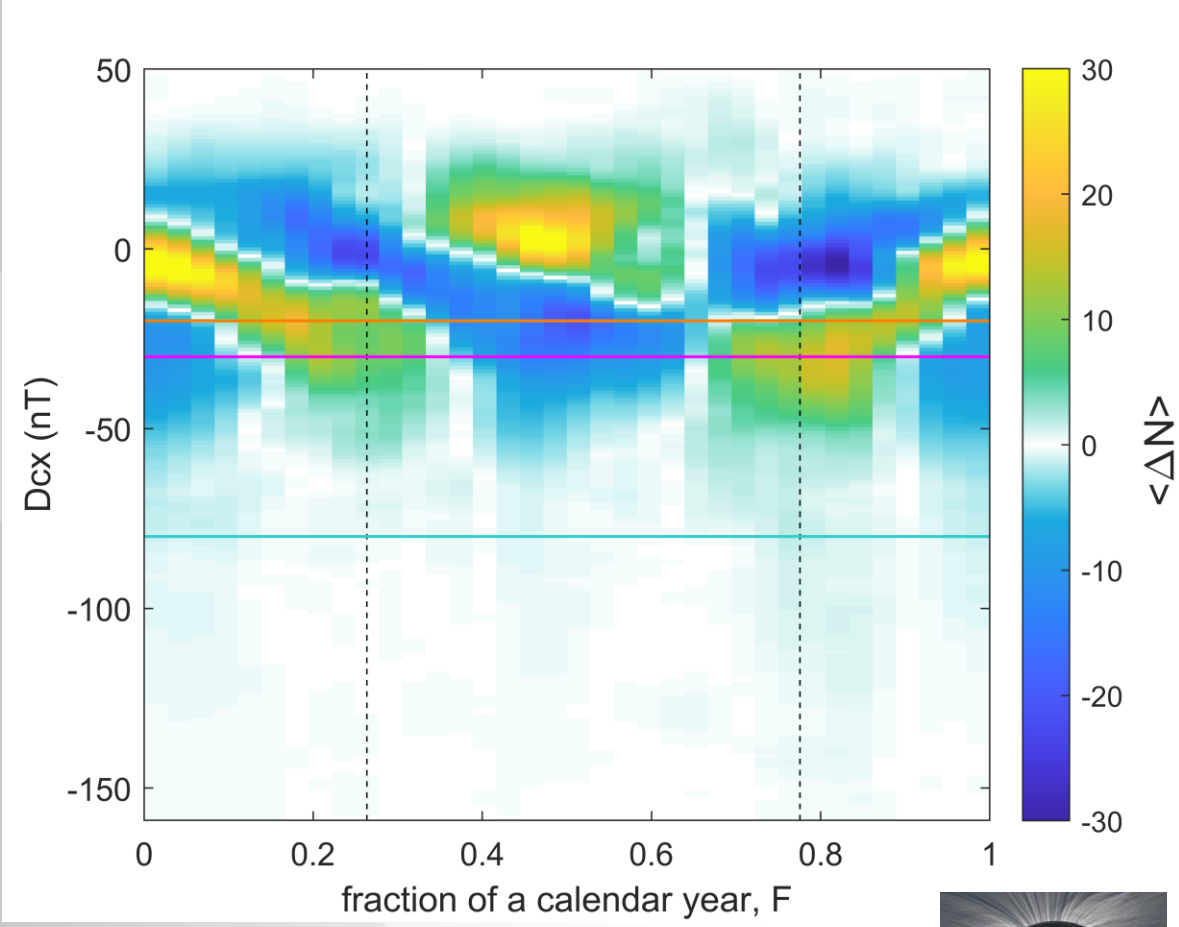
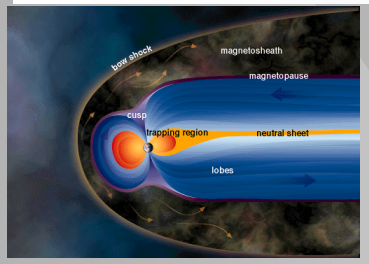
Distributions of hourly ΔDcx

(data for 1996-2024, inclusive)

- Semi- annual effect mainly at small |Dcx|
- Mode value shift to higher disturbance levels at the equinoxes
- Only very weak semi-annual variation in large events





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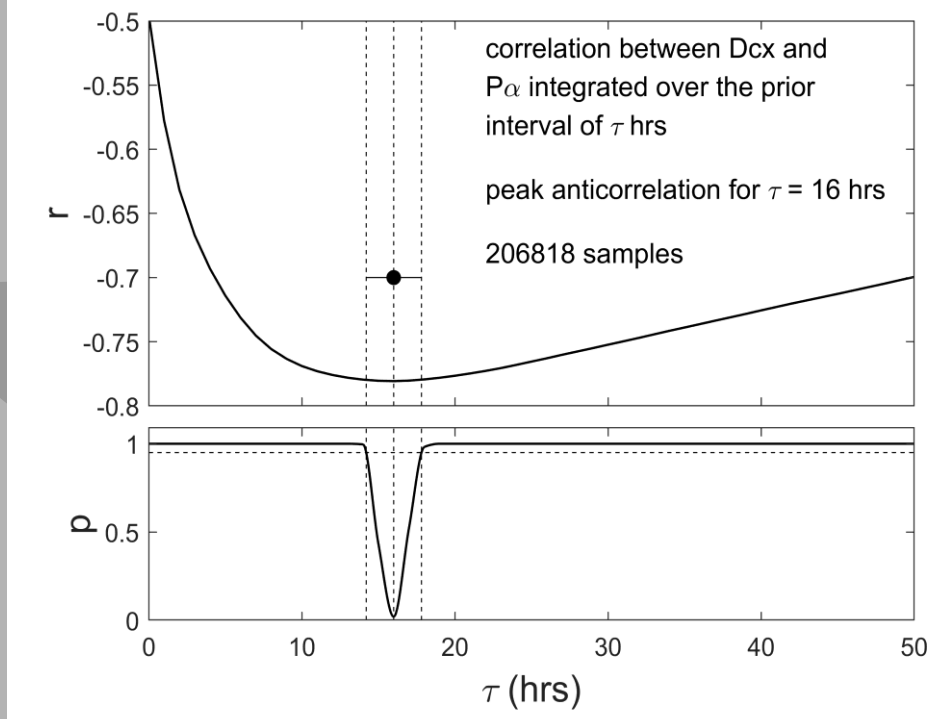
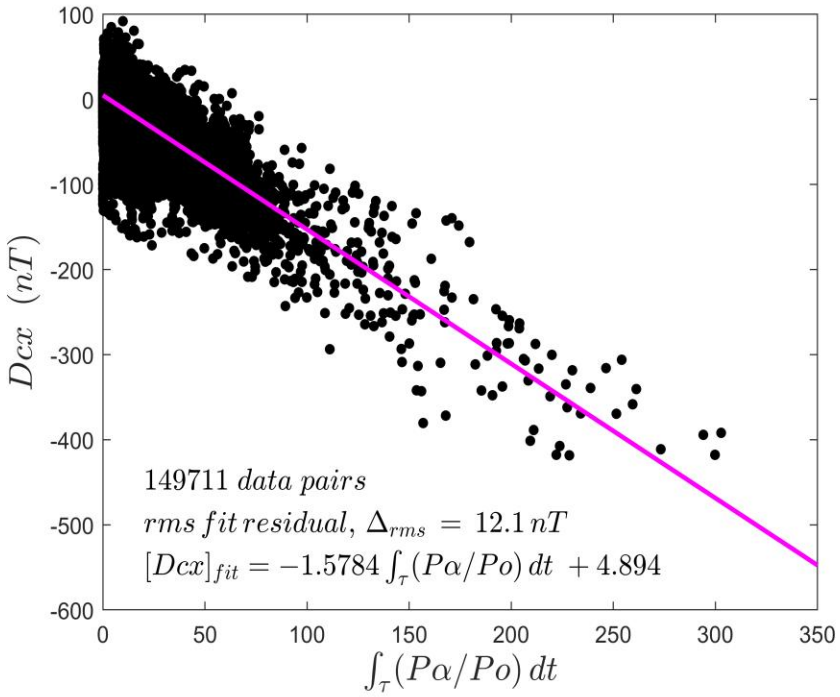
Dcx Response Time to P_α





- Peak anticorrelation of Dcx with Pα integrated over the prior τ = 16 ± 2 hrs.

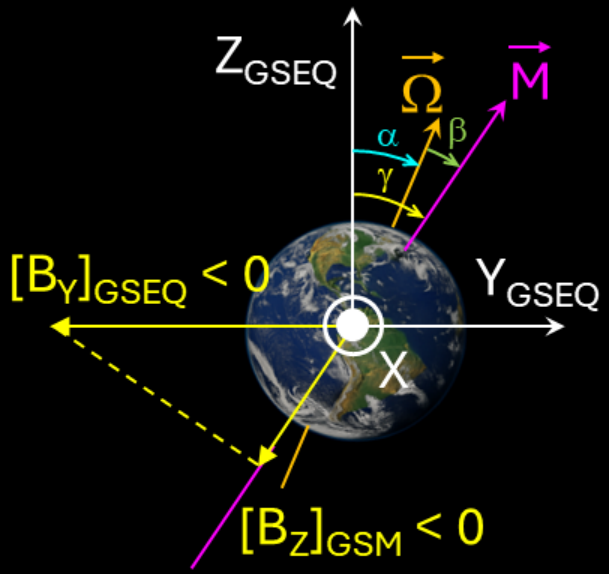
- (uncertainty in optimum τ from the Meng-Z test)



The Russell-McPherron Mechanism

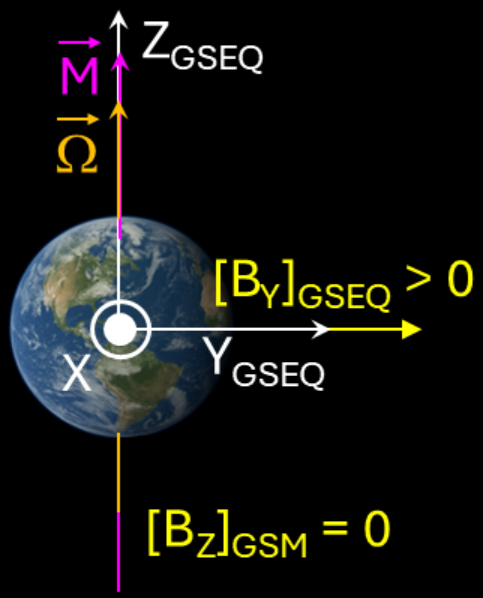
A

March Equinox
(F ≈ 0.22)
at UT≈22hrs
negative IMF $[B_Y]_{GSEQ}$
gives southward IMF in GSM



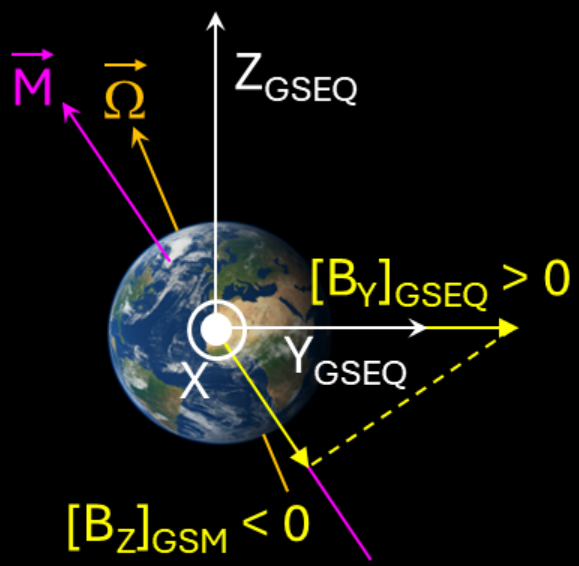
B

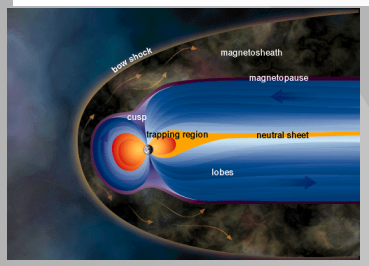
Solstices
(F ≈ 0.48 or ≈ 0.98)
at UT ≈ 4 or UT ≈ 16 hrs
IMF $[B_Y]_{GSEQ}$ has no effect
on southward IMF in GSM



C

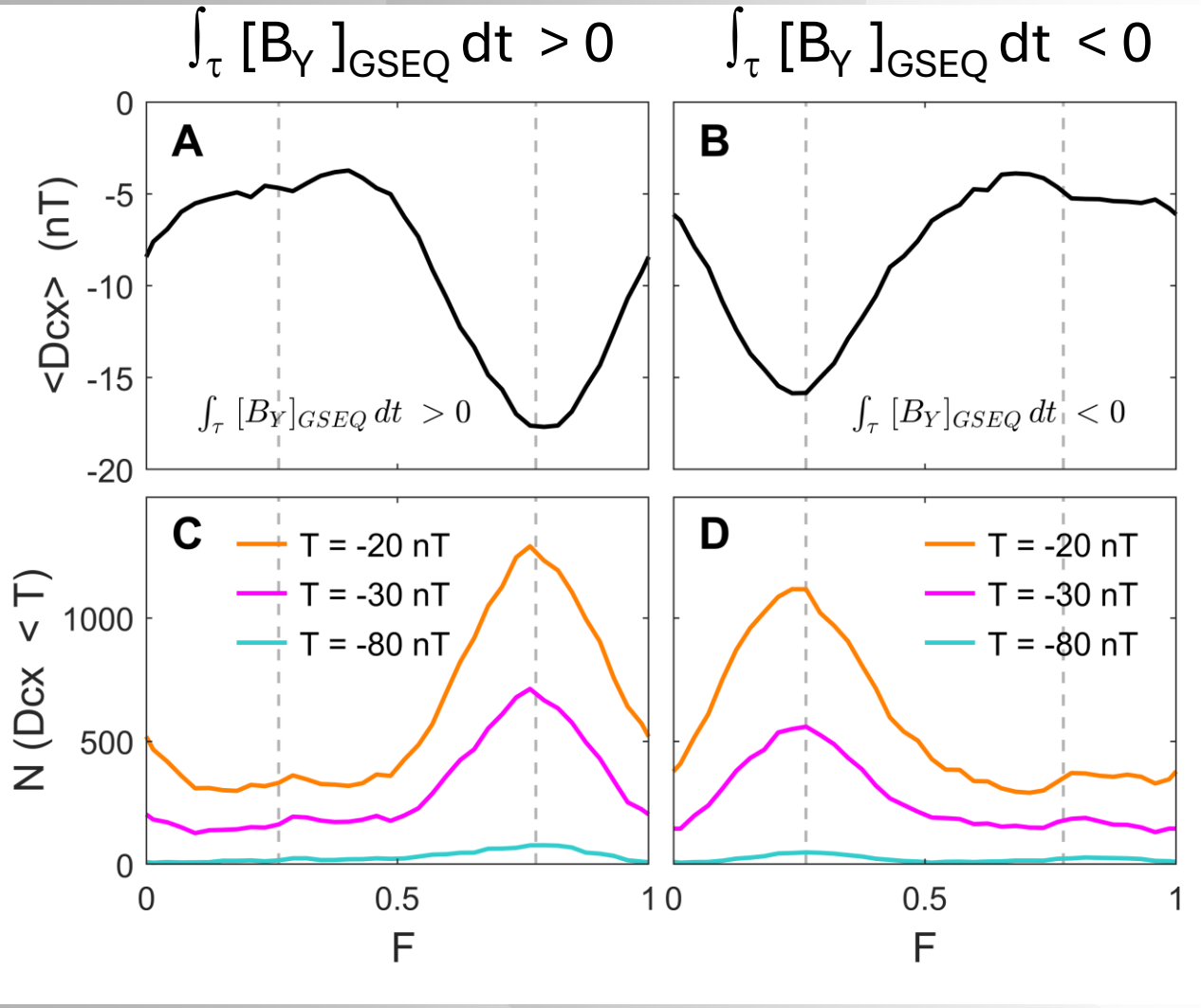
September Equinox
(F ≈ 0.73)
at ~10hrs UT
positive IMF $[B_Y]_{GSEQ}$
gives southward IMF in GSM



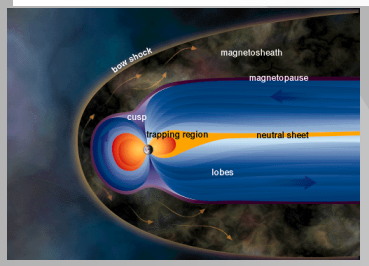


Key test of the R-M effect:

Separating by the IMF B_Y component in GSEQ



- Which of the equinoxes is enhanced depends in IMF $[B_Y]_{GSEQ}$ polarity in the way that is (uniquely) predicted by R-M
- September peak larger as large $[B_Y]_{GSEQ} > 0$ more common in this 1996-2024 interval



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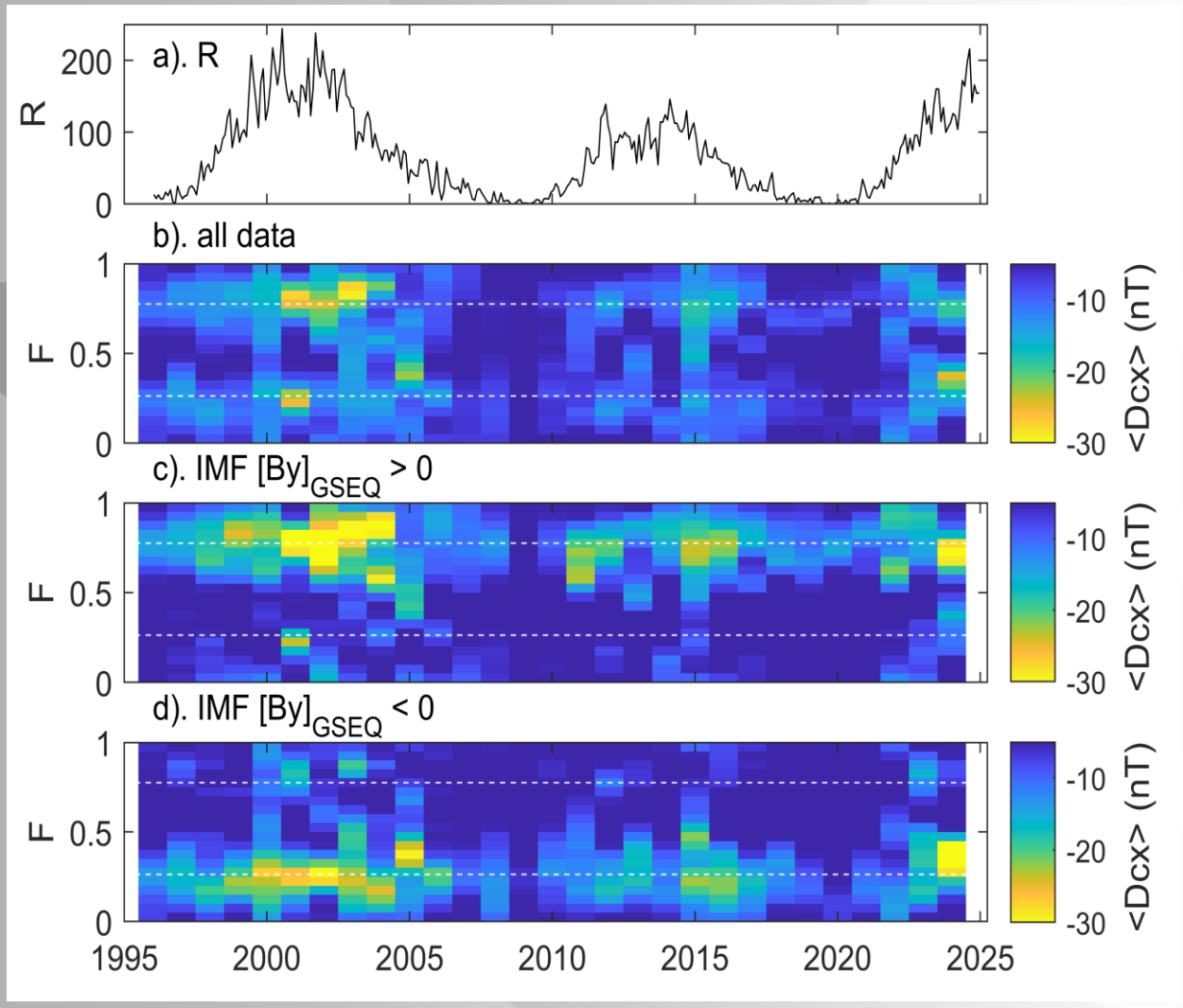
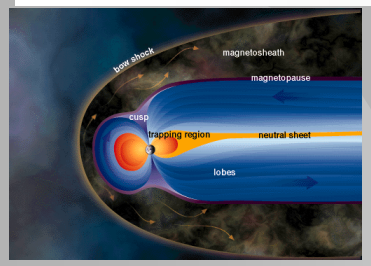


- Effect seen in all years

all data

$\int_\tau [B_Y]_{GSEQ}\, dt > 0$

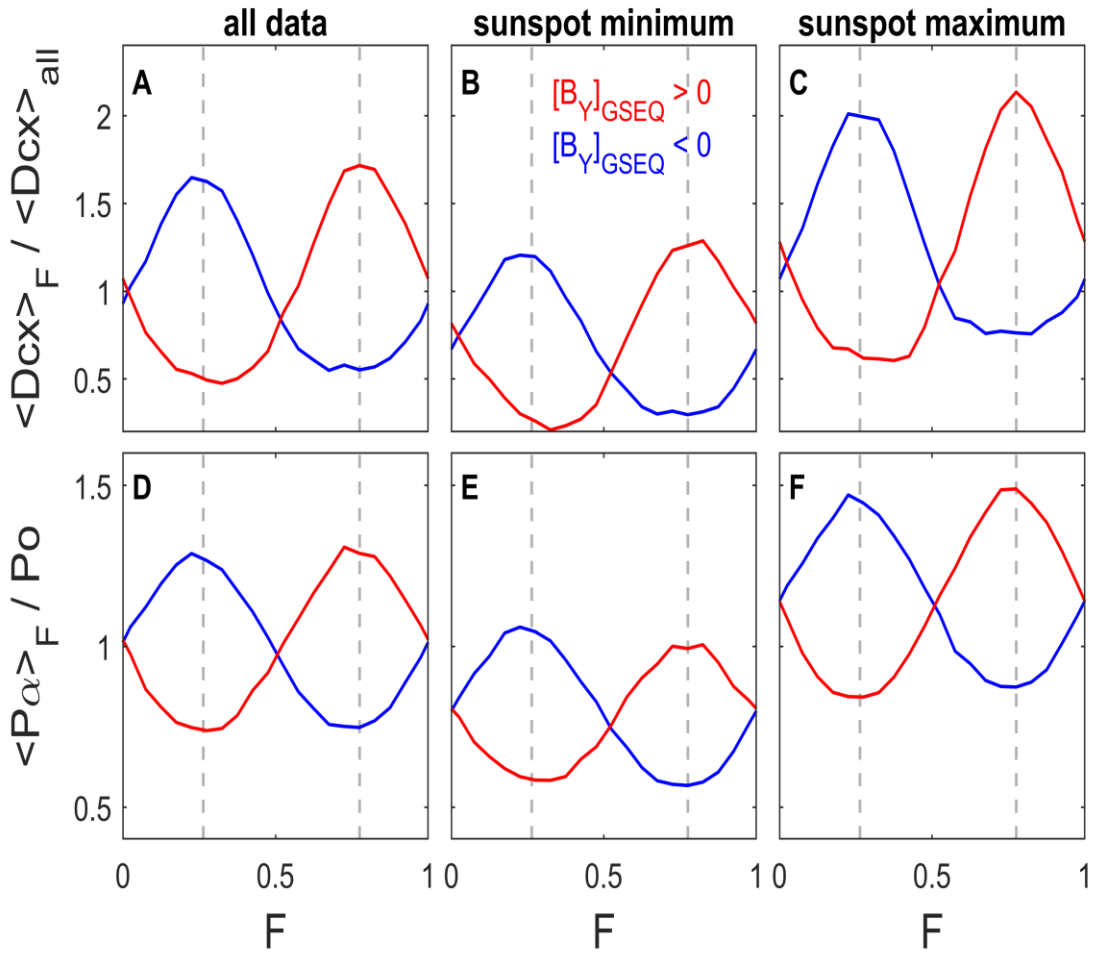
$\int_\tau [B_Y]_{GSEQ}\, dt < 0$



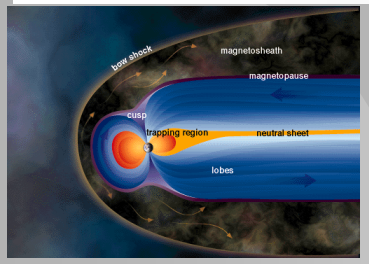
Key test of the R-M effect:

Separating by the IMF B_Y component in GSEQ

$\int_\tau [B_Y]_{GSEQ}\, dt > 0$ $\int_\tau [B_Y]_{GSEQ}\, dt < 0$

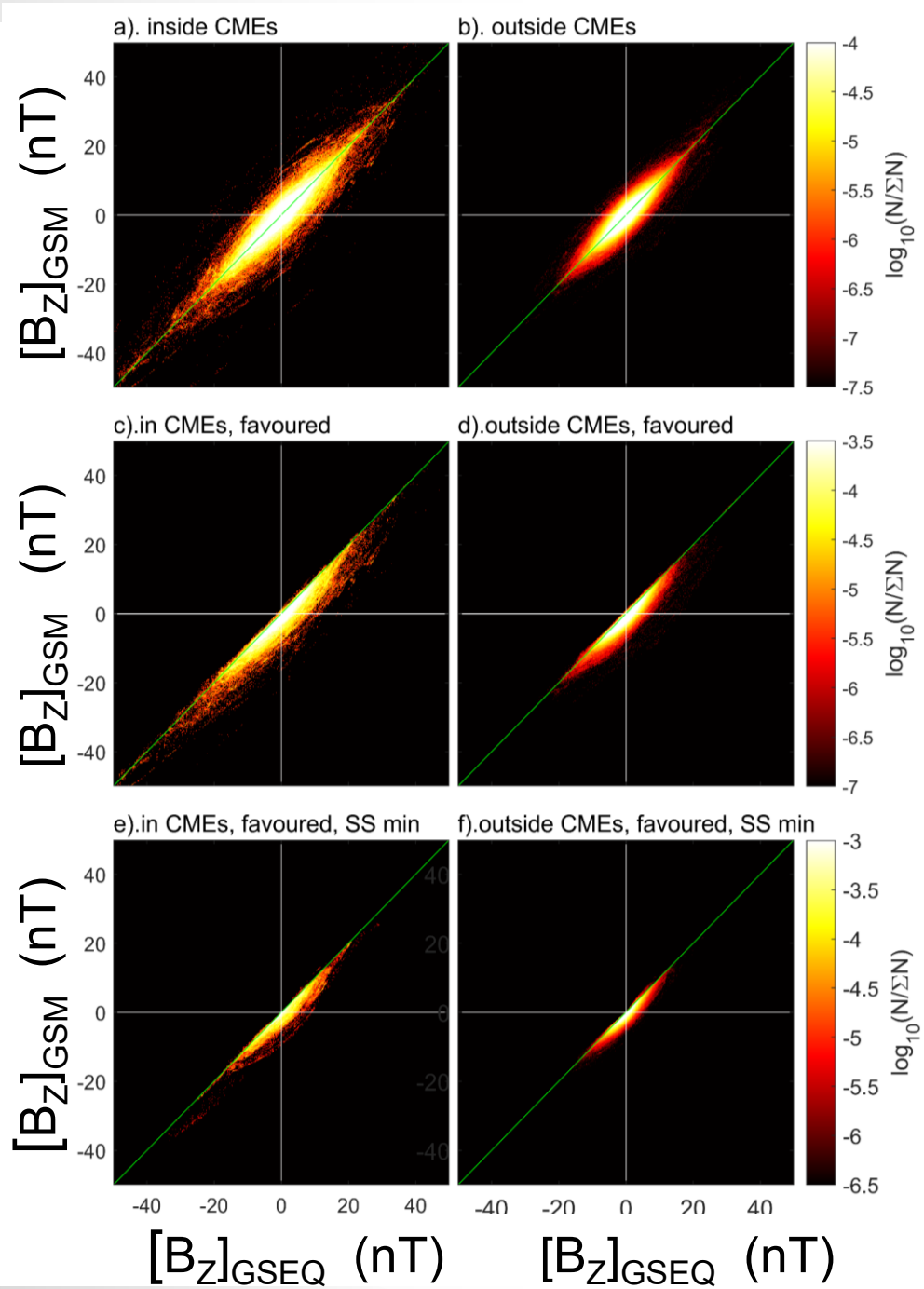


- Fractional variations in Dcx mimic those in $\int_\tau P_\alpha\, dt$
- But mimima in $<Dcx>_F/<Dcx>_{all}$ slightly less deep because for small P_α Dcx can be positive as well as negative



Storms, CMEs & R-M

- R-M works by increasing $|[B_z]_{GSM}|$ over $|[B_z]_{GSEQ}|$ - i.e. broadening the pattern in these plots of 15,585,594 1-minute data points
- Data here sorted into inside CMEs (including sheaths) and outside them using the Richardson list
- Largest negative $[B_z]_{GSM}$ is always when $[B_z]_{GSEQ}$ is large & negative and that is in CME events





So how much does the R-M mechanism contribute to storms?

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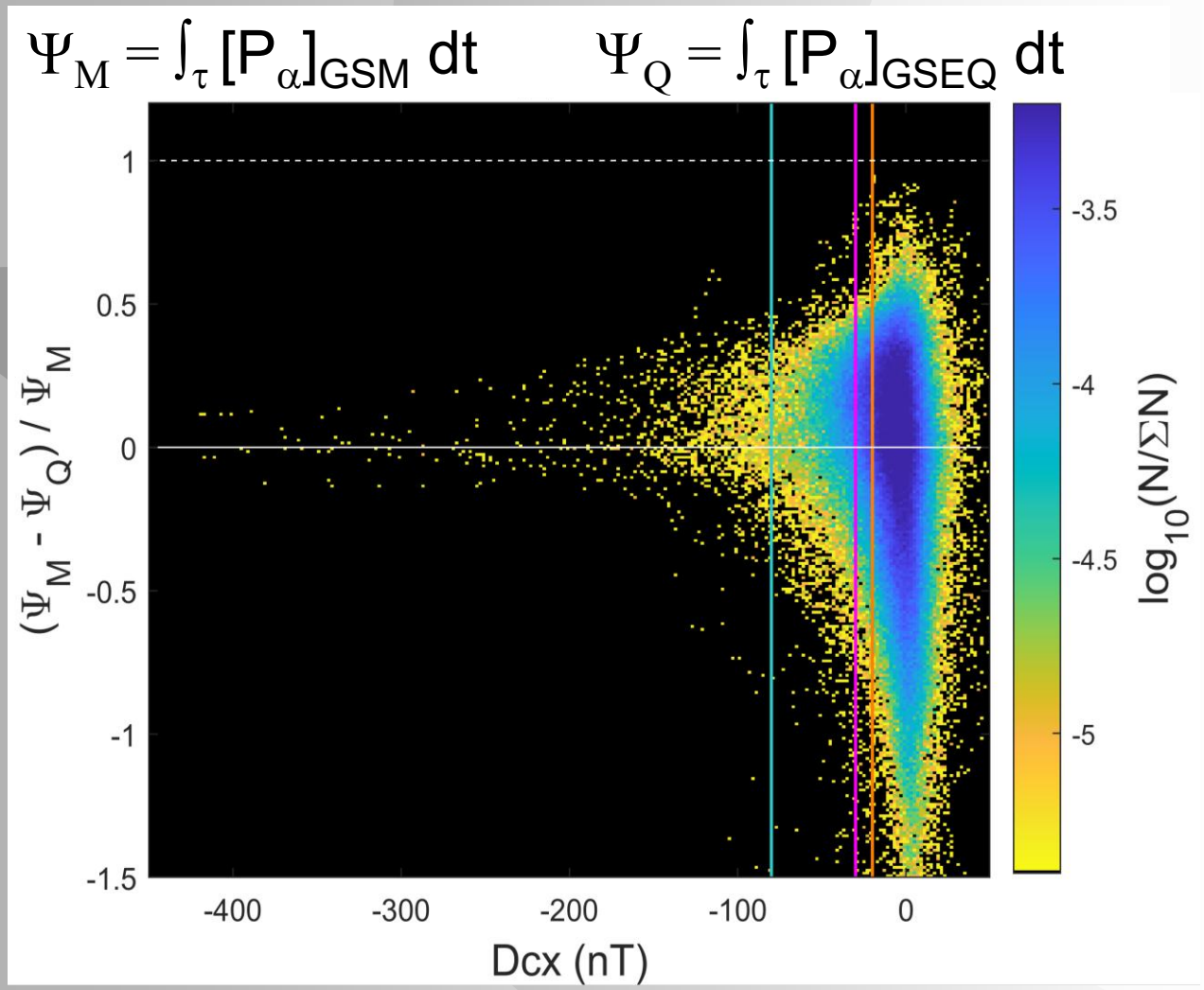
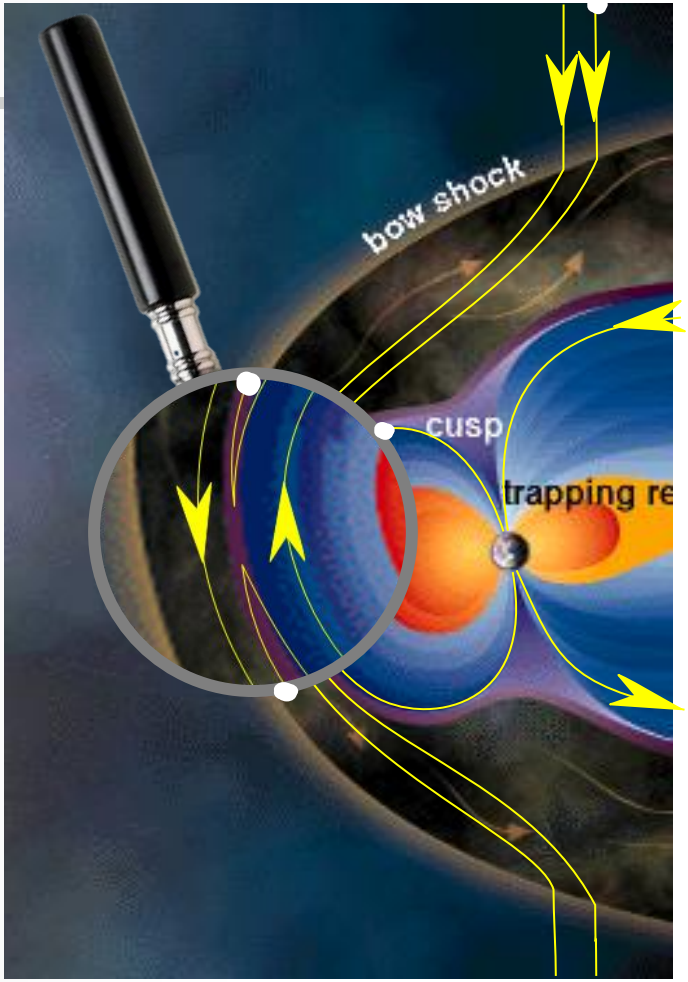


- $(\Psi_M - \Psi_Q)/\Psi_M$ is the fractional contribution of the R-M effect to the total power input to the m'sphere
- For largest storms R-M is adding about 10%
- No Dcx < 0 is 100% caused by the R-M effect



Conclusions



- Coupling functions are very valuable and will be important in the future for forecasting terrestrial space weather and for studies of exoplanets

- The most valuable ones will be theory based and less dependent on empirical fits – but it needs to be the correct theory and there are pitfalls in their generation

- As an example of their use, they show the R-M effect contributes < 10% to large storms – the >90% being the southward IMF in what the sun throws at us (in CME events)



This talk has drawn on the following papers:



Lockwood, M. (2022) Solar wind – magnetosphere coupling functions: pitfalls, limitations and applications, Space Weather, 20, e2021SW002989, doi: 10.1029/2021SW002989

Lockwood, M. and K.A. McWilliams (2021b) On optimum solar wind – magnetosphere coupling functions for transpolar voltage and planetary geomagnetic activity, J. Geophys. Res. Space Phys., 126, e2021JA029946, doi 10.1029/2021JA029946

Lockwood, M. (2019) Does adding solar wind Poynting flux improve the optimum solar wind-magnetosphere coupling function? J. Geophys. Res. (Space Physics), 124 (7), 5498-5515, doi: 10.1029/2019JA026639 (2019)

Finch, I. and M. Lockwood (2007) Solar wind-magnetosphere coupling functions on timescales of 1 day to 1 year, Annales Geophys., 25, 495-506, doi: 10.5194/angeo-25-495-2007

Cowley, S. W. H. (1991). Acceleration and heating of space plasmas—Basic concepts. Annales Geophysicae, 9, 176–187.

Lockwood, M., S. Bentley, M.J. Owens, L.A. Barnard, C.J. Scott, C.E. Watt, and O. Allanson (2019) The development of a space climatology: 1. Solar-wind magnetosphere coupling as a function of timescale and the effect of data gaps, Space Weather, 17, 133-156, doi: 10.1029/2018SW001856 (2019)

Ebihara, Y., T. Tanaka, & N. Kamiyoshikawa, (2019). New diagnosis for energy flow from solar wind to ionosphere during substorm: Global MHD simulation. Journal of Geophysical Research: Space Physics, 124, 360–378. doi: 10.1029/2018JA026177

Lockwood, M., A. Chambodut , I. D. Finch, L. A. Barnard , M. J. Owens and C. Haines (2019) Time-of-day / time-of-year response functions of planetary geomagnetic indices, J. Space Weather Space Clim., 9, A20, doi: 10.1051/swsc/2019017 (2019)

Lockwood, M. and K.A. McWilliams (2021b) A survey of 25 years' transpolar voltage data from the SuperDARN radar network and the Expanding–Contracting Polar Cap model, J. Geophys. Res., 126, e2021JA029554, doi: 10.1029/2021JA029554 (2021)

Lockwood, M. and S.W.H. Cowley, (2022) Magnetosphere-Ionosphere coupling: implications of non-equilibrium conditions, Frontiers Astron. and Space Sci., 9, 908571, doi: 10.3389/fspas.2022.908571 (2022)

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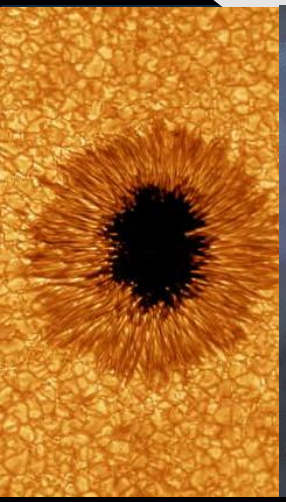







THANK YOU FOR LISTENING

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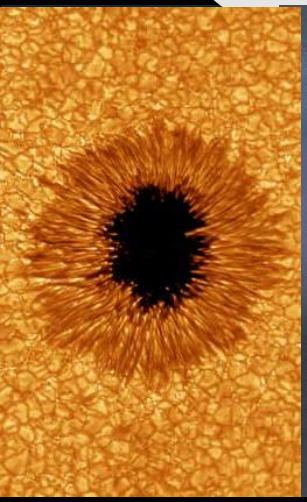

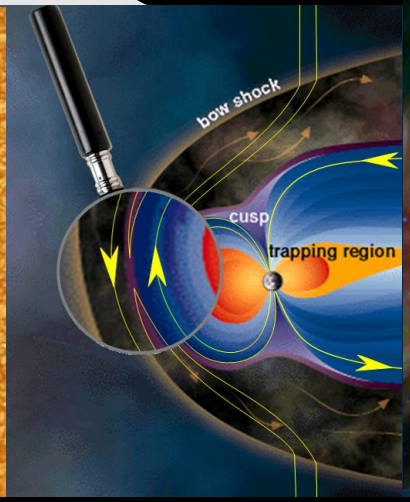





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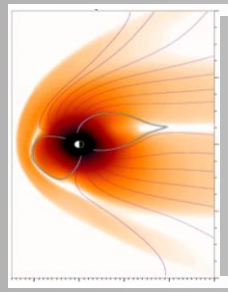

Timescale, averaging and weighting

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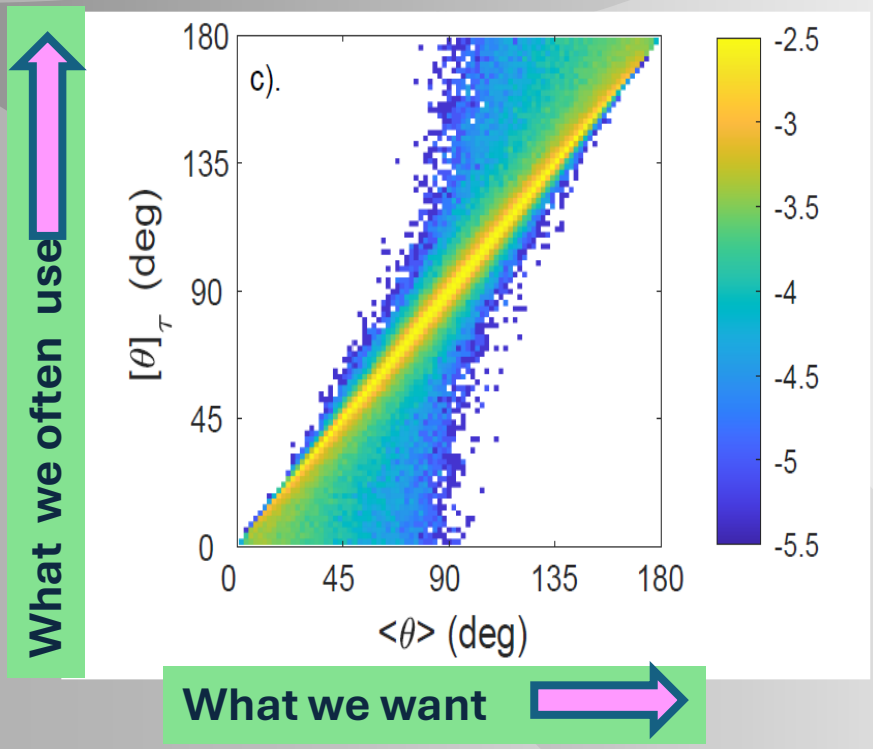
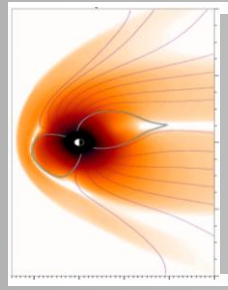
- Big part of problem lies in using averaged B_x and B_y components to compute and θ (and, less importantly $B_\perp$)
- Solved by computing θ at high time resolution and then averaging *(e.g. McPherron et al., 2015)*



- We want
  $\langle\theta\rangle = \langle\tan^{-1}(B_Z/|B_Y|)\rangle$
- Many folk (incorrectly) use
  $[\theta] = \tan^{-1}(\langle B_Z\rangle/\langle|B_Y|\rangle)$





Timescale, averaging and weighting: $\langle x^p \rangle_\tau \neq \langle x \rangle_\tau^p$

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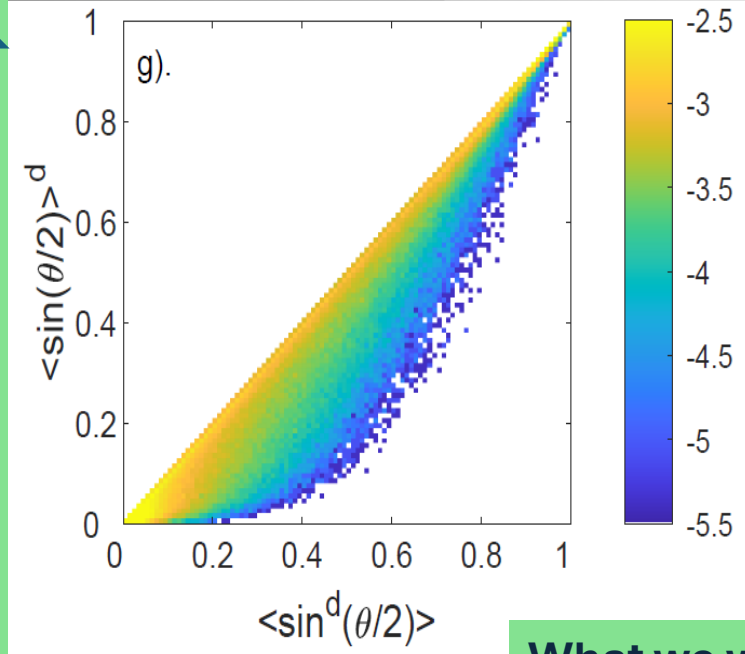
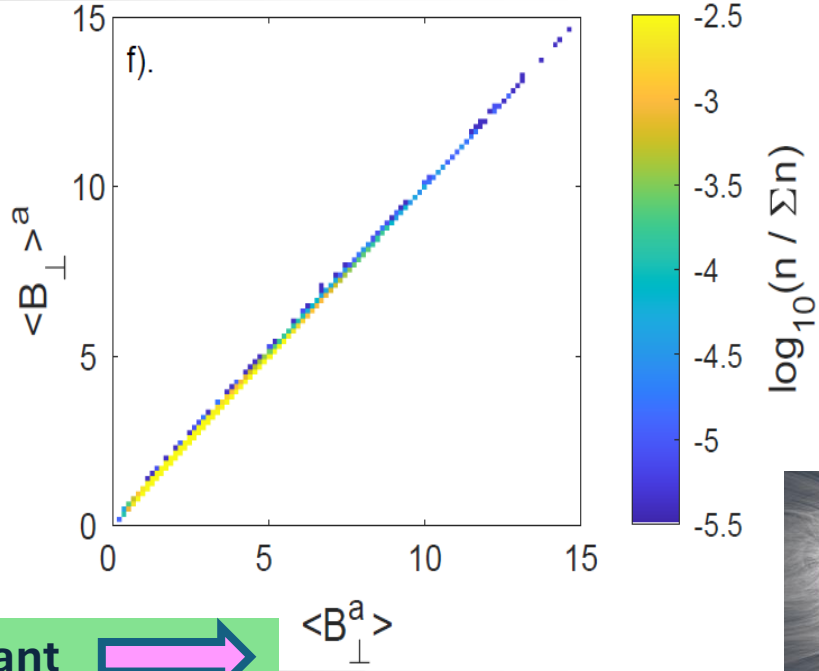
- But there is another problem which affects $\sin^d(\theta/2)$ most because of its much greater variability within the hour
- For $p > 1$ the Hölder ("power") mean $[\langle x^p \rangle_\tau]^{1/p}$ exceeds arithmetic mean $\langle x \rangle_\tau$ - and the difference increases with p and τ
- Hence for $p > 1$, $\langle x^p \rangle_\tau > \langle x \rangle_\tau^p$ (and for $p < 1$, $\langle x^p \rangle_\tau < \langle x \rangle_\tau^p$)

What we often use



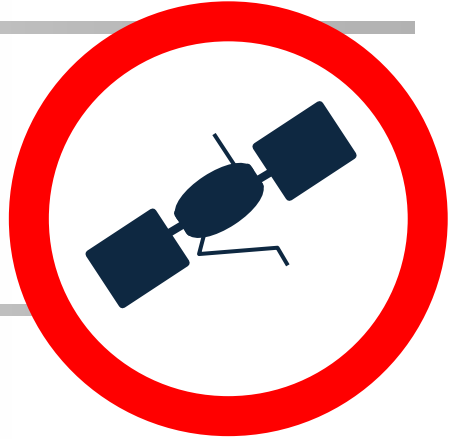


What we want

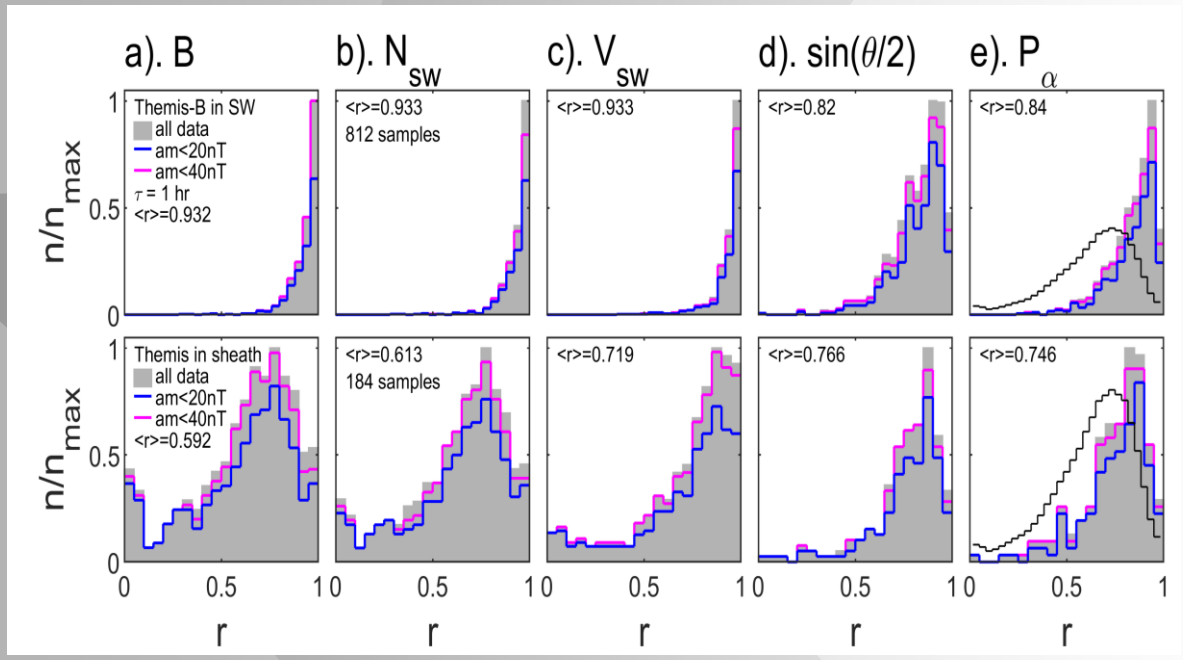




Correlations between data from L1 and Themis-B just outside magnetosphere



Distributions of peak correlations at optimum lag for 1-hour data



- Same format plot as for the 1-minute data

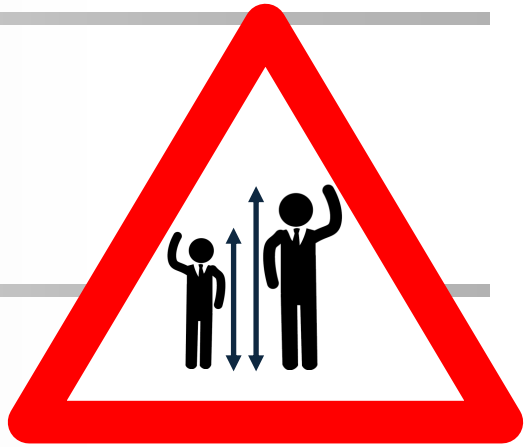
- *From: Lockwood, M. (2022) Solar wind – magnetosphere coupling functions: pitfalls, limitations and applications, Space Weather, 20, e2021SW002989, doi: 10.1029/2021SW002989 (2022)*

- Same conclusions apply as for the 1-minute data
- All corelations considerably better for these lower resolution data





Best-fits compared to simple theories



- all C_f made using best-practice "combine-then-average" at optimum lag
- compare with simple theories for coupling of energy (for am) and voltage (for Φ_{PC})

T	lag, δt (min)	C_f	optimum values					
			d	r_p	r_p^2	a	b	c
Φ_{PC}	18.5 ±1.3	best fit	2.50±0.07	0.865	0.748	0.642±0.019	0.018±0.008	0.550±0.047
		Φ'_{PC} for constant η	4	0.823	0.677	1	−0.167	0.667
am	47.0 ±4.0	best fit	3.00±0.22	0.858	0.736	0.802±0.022	0.360±0.012	2.560±0.072
		P_α for α = 0.4	3	0.852	0.725	0.800	0.267	1.533

- Note that best C_f different for am and Φ_{PC}
- There is **no such thing** as a "universal" C_f





SuperDARN radar observations of transpolar voltage Φ_{PC} 1995-2020

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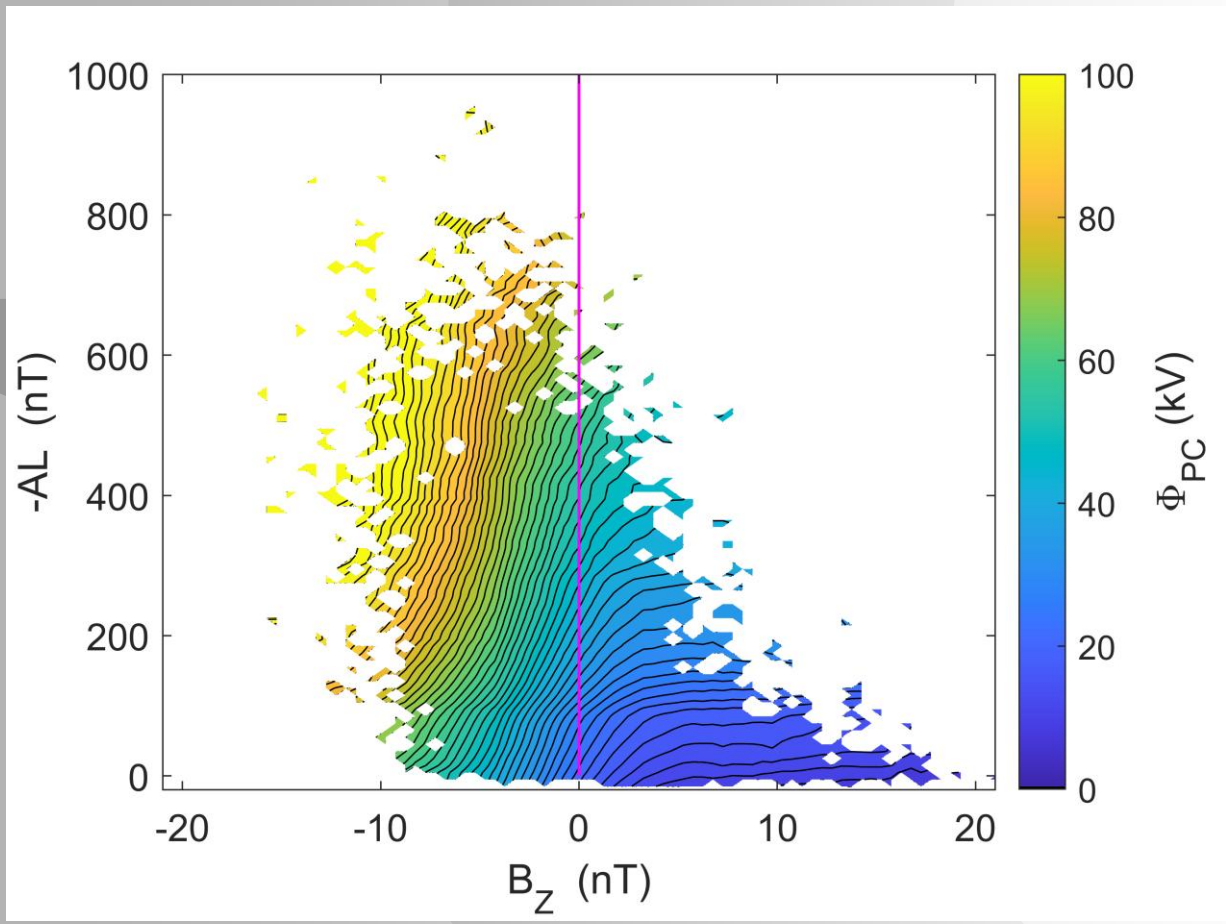
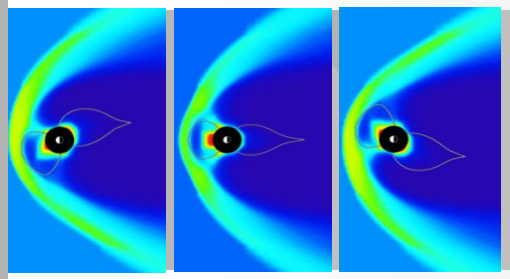


- Φ_{PC} is contoured as a function of IMF B_z (along x axis) and $-AL$ (along y axis)
- For $B_z << 0$, Φ_{PC} is dominated by the magnetopause reconnection voltage Φ_D
- For $B_z >> 0$, Φ_{PC} is dominated by the tail reconnection voltage Φ_N
- general B_z shows Φ_{PC} is a mix of Φ_D & Φ_N

- Φ_D responds to SW within ~5min & Φ_N and AL after ~40min

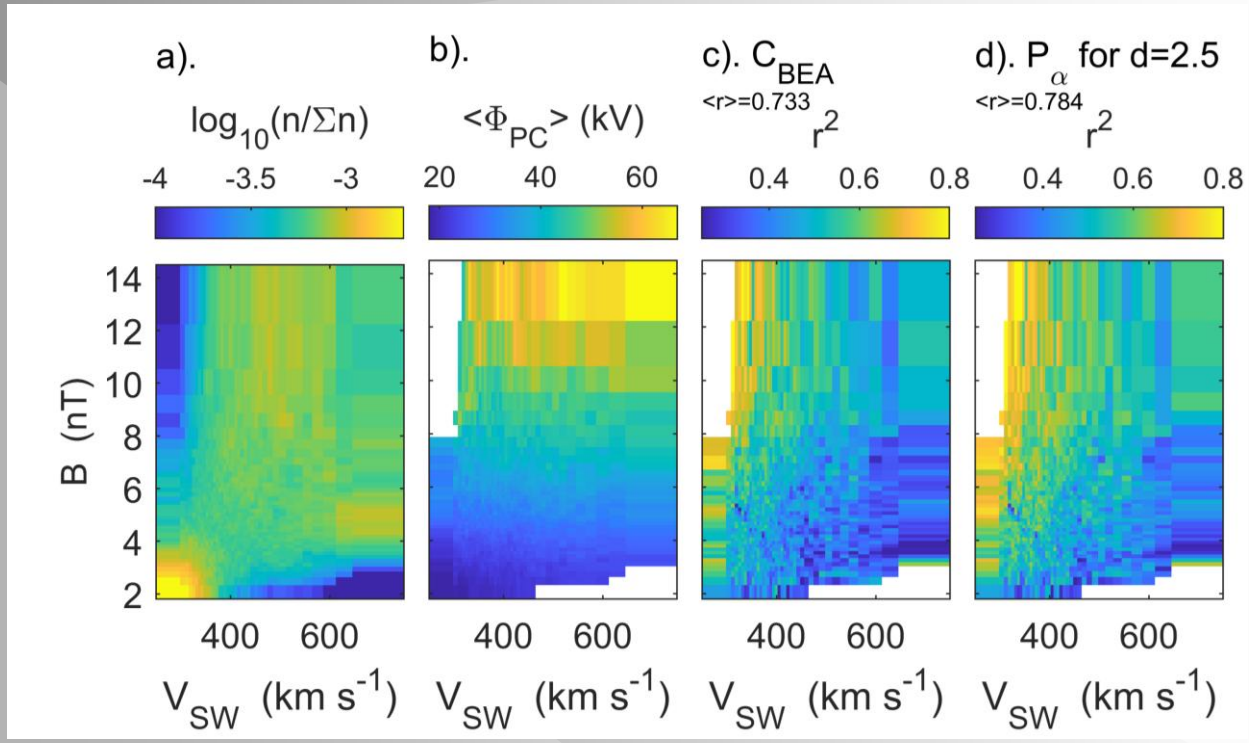
Lockwood and McWilliams (2021) DOI: 10.1029/2021JA029554





Note that correlations are not uniform over parameter space

- 25 years of transpolar voltage correlated with C_{BEA} and P_{α}
- 40 quantile ranges of both B and V_{SW}
- correlations best for high B and low V_{SW}
- correlations poor for low B and high V_{SW}



S6



Conclusions: Pitfalls



- Coupling function reflects errors in IMF orientation caused by data gaps: reject means of insufficient samples
- Distributions and averaging give statistical biases to certain clock angles, so IMF orientation factor must be determined by the linearity condition, not correlation
- need to always "compute-then-average" especially for $F(\theta)$ at large d and τ, and worry about effect of datagaps
- Note that for larger τ the difference between $\langle x^a \rangle$ and $\langle x \rangle^a$ will become significant for ρ_{sw} and then $B_\perp$: the higher persistence of V_{sw} means it will be the least affected