What Do Magnetospheric Physicists Need from a Solar Wind Model?

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Abstract

- Magnetospheric activity is driven by the solar wind dynamic pressure and interplanetary magnetic field. The time constants for this activity vary between a few minutes and a few hours. An accurate prediction of the behavior of various magnetospheric parameters requires data at higher resolution that the shortest time constant. Near the Earth empirical and MHD models of the magnetosphere normally use data at one-minute cadence. To obtain this time resolution it is necessary to monitor the inputs 250 Re upstream of the Earth at the L1 point. When propagated to the Earth such measurements provide 30-60 minutes advance warning. The best empirical L1 to Earth propagation algorithm provides quite accurate values at the bow shock most of the time. Additional lead time would require a solar wind monitor further upstream along the Earth-Sun line. This would be a difficult and expensive observatory to maintain. The further upstream the monitor the less likely it would be that the propagated measurements represent what arrives at the Earth. Even more lead time could be provided by remote observations of the Sun used to initialize a solar wind model. Currently the spatial resolution of MHD models that attempt to do this is 500 Re corresponding to 2 hours of solar wind travel. Empirical models have an even lower time resolution of approximately nine hours. It is a near certainty that such models will never be able to predict the detailed wave form of IMF Bz at the Earth from solar observations and MHD models. The waveform of Bz is a result of many processes both at the Sun and in the intervening solar wind. Waves and structures moving through the solar wind cause the median time between reversals of 1-minute Bz to be only 4 minutes. There is hope, however, that MHD models initialized by observations from a ring of spacecraft around the Sun, and ahead and behind the Earth in Earth orbit, could provide global descriptions of structures such as CIRs and CMEs. Knowledge of the arrival time of these structures could be combined with climatology of these structures to provide an ensemble of possible drivers of activity associated with the structure. From this climatology it is possible to create an ensemble of surrogate time series to drive a model. For each member of the ensemble a different sequence of activity would be created. These could be combined to provide an estimate of the probability that an important parameter will lie in a given range of values.

Important Points

- Magnetospheric activity is mainly driven by the solar wind dynamic pressure and electric field
- These quantities require high time resolution measurement of the solar wind at the magnetopause to provide good input to empirical and physics-based models
- Measurements at L1 must be propagated to magnetopause by some model to provide 30-60 minute lead time
- Additional lead time would require observations from further upstream which after propagation are not likely to be accurate
- It is unlikely that any model based on solar observations will ever be able to accurately predict the IMF Bz at the Earth
- The only hope is to predict the arrival of structures and to use climatology of these structures to provide an ensemble of possible drivers as input to models
- The ensemble of possible outputs provide a method of probabilistic forecast of various magnetospheric parameters

Historical Coupling Functions

Newell, P. T., T. Sotirelis, K. Liou, C.-I. Meng, and F. J. Rich (2007), A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables, *J. Geophys. Res.*, *112*(*A1*), 1-16.

- A literature search by Newell shows a variety of coupling functions that have been related to geomagnetic activity
- The solar wind variables included in these are: B_z (B_s), B_y, (B_t), V, ρ (n, M), θ_c
- Combinations of these variables include: *Poynting flux, electric field, dynamic pressure, clock angle*

Table 1. Twenty Candidate Solar Wind-Magnetosphere Coupling Functions and Their Origins in Roughly Historical Order

Name	Functional Form	Reference
B_z	B_z	*Dungey* [1961]
Velocity	v	*Crooker et al.* [1977]
Density	n	
p	$nv^2/2$	*Chapman and Ferraro* [1931]
Bs	B_z $(B_z < 0)$; 0 $(B_z > 0)$	
Half-wave rectifier	vBs	*Burton et al.* [1975]
ε	$vB^2\sin^4(\theta_c/2)$	*Perrault and Akasofu* [1978]
ε_2	$vB_T^2\sin^4(\theta_c/2)$	Variant on ε
ε_3	$vB\sin^4(\theta_c/2)$	Variant on ε
Solar wind E-field	vB_T	
E_{KL}	$vB_T\sin^2(\theta_c/2)$	*Kan and Lee* [1979]
$E_{KL}^{1/2}$	$[vB_T\sin^2(\theta_c/2)]^{1/2}$	Variant on the Kan-Lee electric field
E_{KLV}	$v^{4/3}B_T\sin^2(\theta_c/2)p^{1/6}$	*Vasyliunas et al.* [1982]
E_{WAV}	$vB_T\sin^4(\theta_c/2)$	*Wygant et al.* [1983]
E_{WAV}^2	$[vB_T\sin^4(\theta_c/2)]^2$	Variant on E_{WAV}
$E_{WAV}^{1/2}$	$[vB_T\sin^4(\theta_c/2)]^{1/2}$	Variant on E_{WAV}
E_{WV}	$v^{4/3}B_T\sin^4(\theta_c/2)p^{1/6}$	*Vasyliunas et al.* [1982]
E_{SR}	$vB_T\sin^4(\theta_c/2)p^{1/2}$	*Scurry and Russell* [1991]
E_{TL}	$n^{1/2}v^2B_T\sin^6(\theta_c/2)$	*Temerin and Li* [2006]
$d\Phi_{MP}/dt$	$v^{4/3}B_T^{2/3}\sin^{8/3}(\theta_c/2)$	This paper

Two new solar wind-magnetosphere coupling functions

Newell, P. T., T. Sotirelis, K. Liou, C.-I. Meng, and F. J. Rich (2007), A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables, *J. Geophys. Res.*, *112*(*A1)*, 1-16.

$$R = d\Phi_{MP}/dt = V^{4/3} B_T^{2/3} \sin^{8/3}(\theta_c/2)$$

Borovsky (2008), The Rudiments of a Theory of Solar-Wind/Magnetosphere Coupling Derived from First Principles, Journal of Geophysical Research, in press.

$$R = 1.6\sin(\theta/2)\rho_0 V_0^2 (1+0.5M_{ms}^{-2})(1+\beta_s)^{-1/2}\left[C\rho_0 + (1+\beta_s)^{-1/2}\rho_m\right]^{-1/2}\left[(1+\beta_s)^{+1/2}+1\right]^{-1/2}$$

$R \Rightarrow$ Reconnection rate and

ρ_o is the mass density of the solar wind upstream of the bow shock,

V_0 is the velocity of the solar wind upstream of the bow shock,

C is the compression ratio of the bow shock,

β_s is the plasma - β value of the magnetosheath plasma near the nose, and

M_{ms} is the magnetosonic Mach number of the solar wind.

Supplementary Relations for Borovsky Formula

$$\beta_s = 3.2\times10^{-2} M_A^{1.92}$$

$$C = \{[1/4]^6 + [1/(1 + 1.38\log_e(M_A))]^6\}^{-1/6}$$

$$M_{ms} = v_o / ((B_o/\mu_o\rho_o) + 5P_o/3\rho_o)^{1/2}$$

$$M_A = v_o (\mu_o\rho_o)^{1/2} / B_o \qquad ,$$

- Needless to say – the Borovsky formula is NOT intuitive!
- It is difficult to see how VBs can work as well as it does if this is the correct relation

Forecasting from Measurements at L1

- Continuous measurement of plasma and magnetic field
- Continuous real time communication with Earth
- Multiple downlink stations with interconnectivity to central database
- Short delays in processing data into calibrated values in GSE coordinates
- Model to propagate measurements to bow shock and convert to GSM coordinates at uniform cadence
- Model to transfer data through the magnetosheath to magnetopause
- Optimum coupling functions for different indices
- Empirical or physics-based models of magnetospheric activity

An Empirical L1 to Bow Shock Model

- Start with calibrated measurements in GSE coordinates at clock cadence (1-minute)
- Use Modified Minimum Variance Method to calculate arrival time at Earth of each sample of solar wind and IMF
- Sort delayed samples according to arrival time at bow shock
- Interpolate arrival times to clock cadence
- Transform to GSM coordinates
- Calculate coupling functions from propagated data
- Run magnetospheric model to predict a useful quantity

Solar Wind Propagation Delays

- The interface between two flux tubes is assumed to be a planar interface on the scale of the distance between L1 and Earth
- The interface is characterized by its normal $\hat{n}$
- In a time Δt the solar wind convects the interface along the normal displacing it by an amount

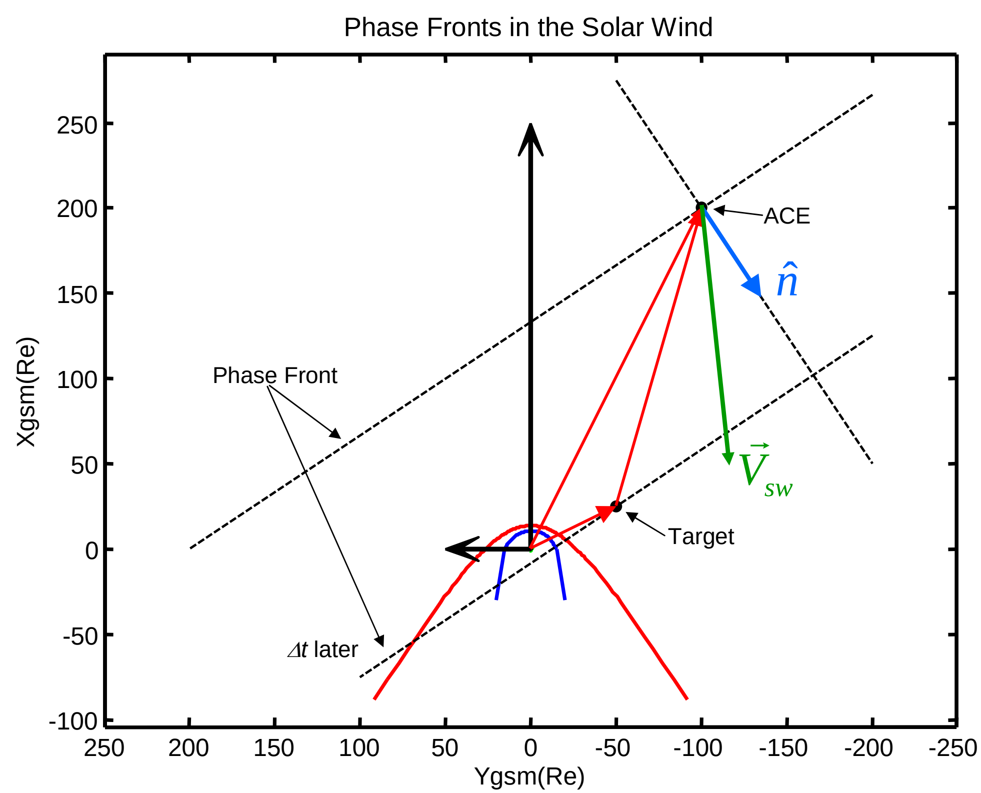
$$\left(\vec{V}_{sw} \cdot \hat{n}\right)\Delta t$$

- The separation of the two spacecraft along the normal is

$$\left(\vec{P}_T - \vec{P}_{ACE}\right)\cdot \hat{n}$$

- Equate these distances to obtain the time delay

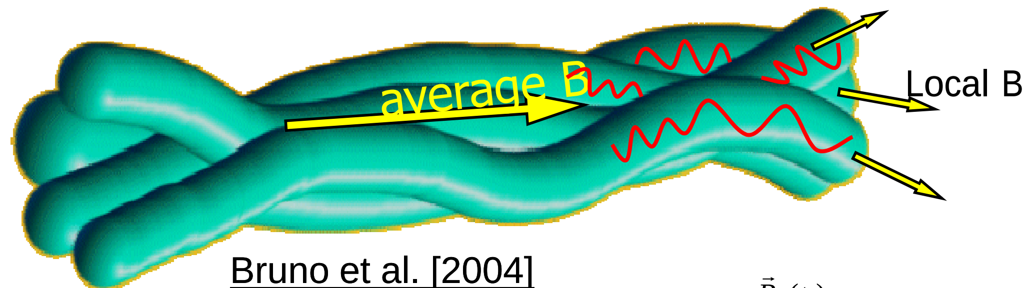
$$\left(\vec{V}_{sw} \cdot \hat{n}\right)\Delta t = \left(\vec{P}_T - \vec{P}_{ACE}\right)\cdot \hat{n}$$



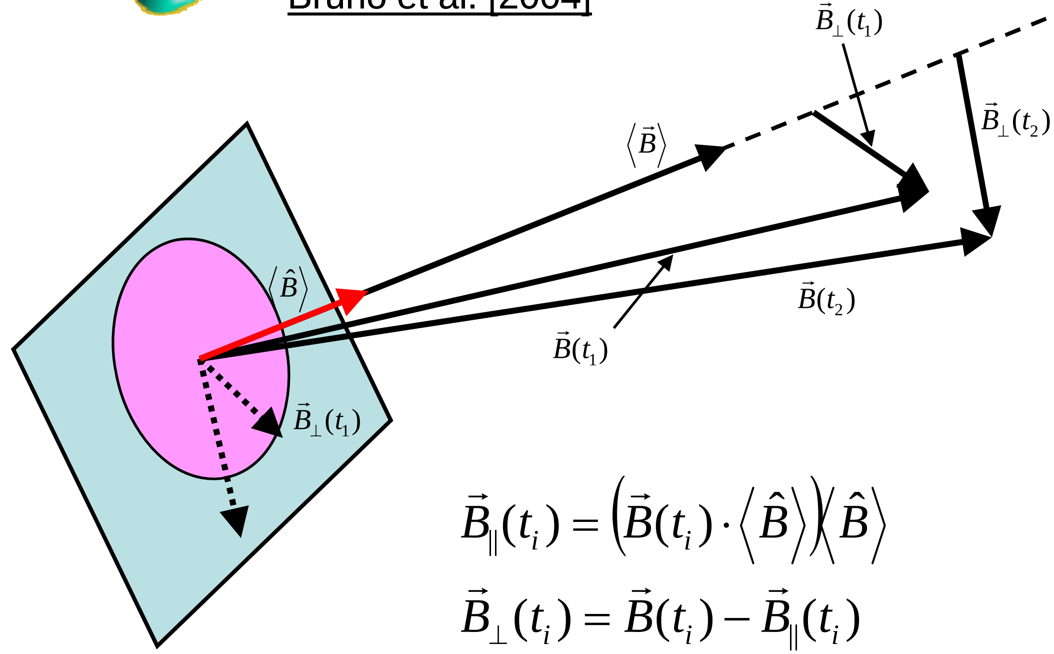
$$\Delta t = \frac{\left(\vec{P}_T - \vec{P}_{ACE}\right)\cdot \hat{n}}{\left(\vec{V}_{sw} \cdot \hat{n}\right)}$$

A Possible Structure of Solar Wind

- Postulate that the solar wind consists of multiple adjacent flux tubes roughly aligned with the Parker spiral
- At any instant the direction of a flux tube is determined by the mean field
- As the monitor passes from one flux tube to another due to solar wind flow the field rotates slightly
- In a short interval this rotation is about an axis orthogonal to the mean field
- The axis of rotation can be found by minimum variance analysis of the magnetic field orthogonal to the mean field



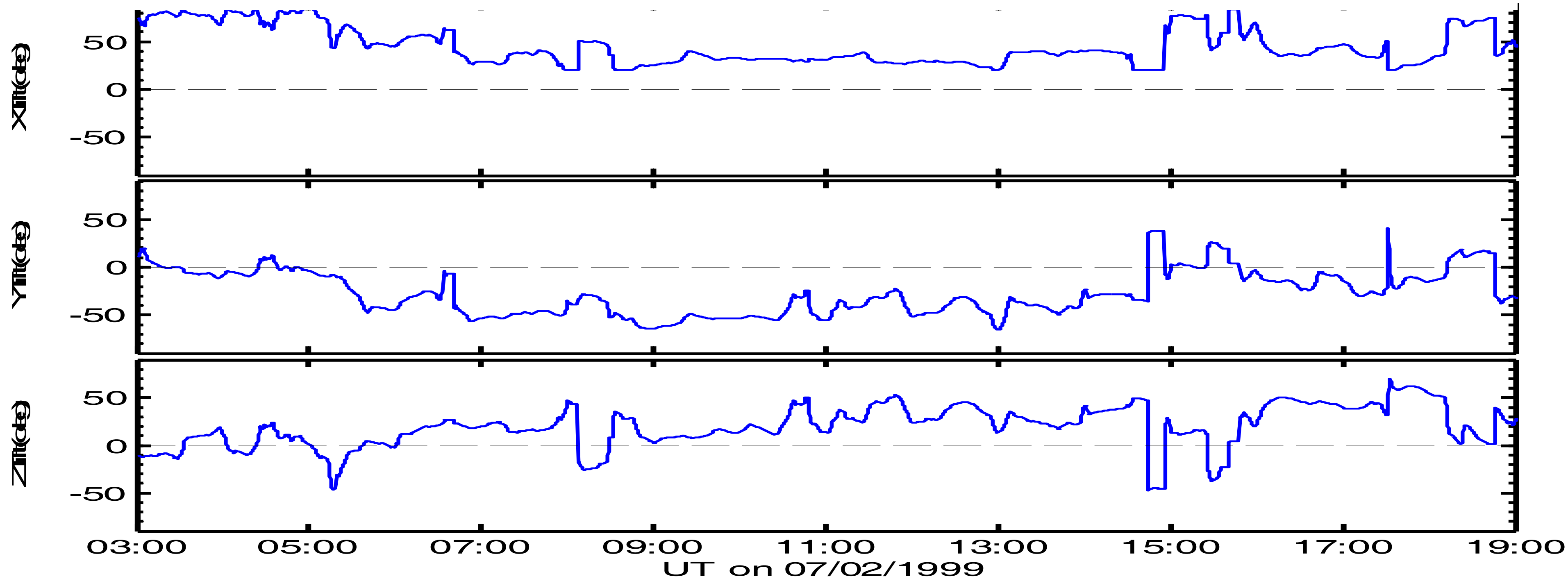
Bruno et al. [2004]



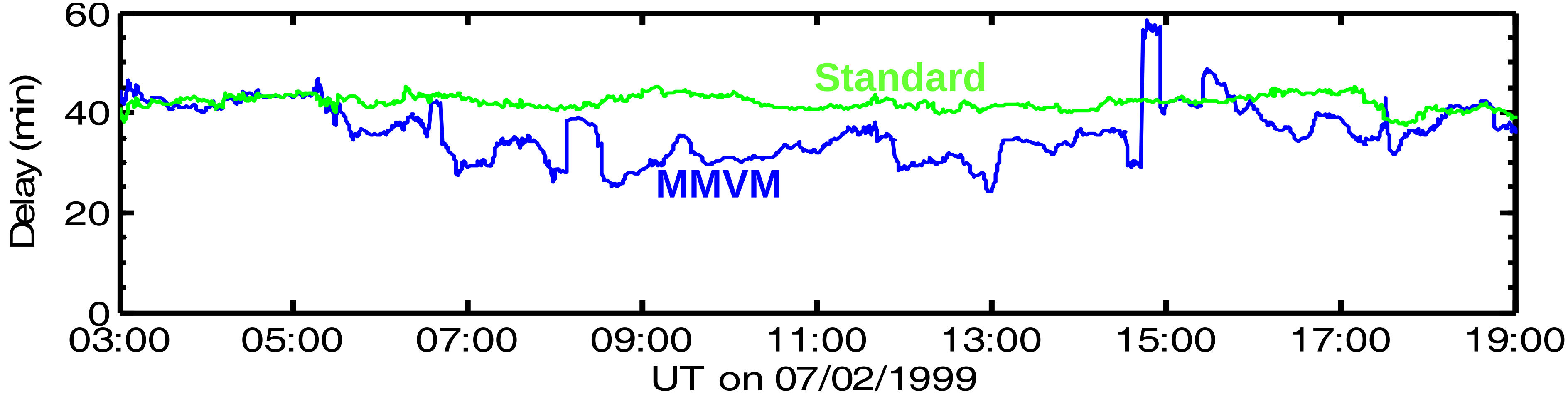
$$\vec{B}_\parallel(t_i) = \left(\vec{B}(t_i) \cdot \langle \hat{B} \rangle\right) \langle \hat{B} \rangle$$

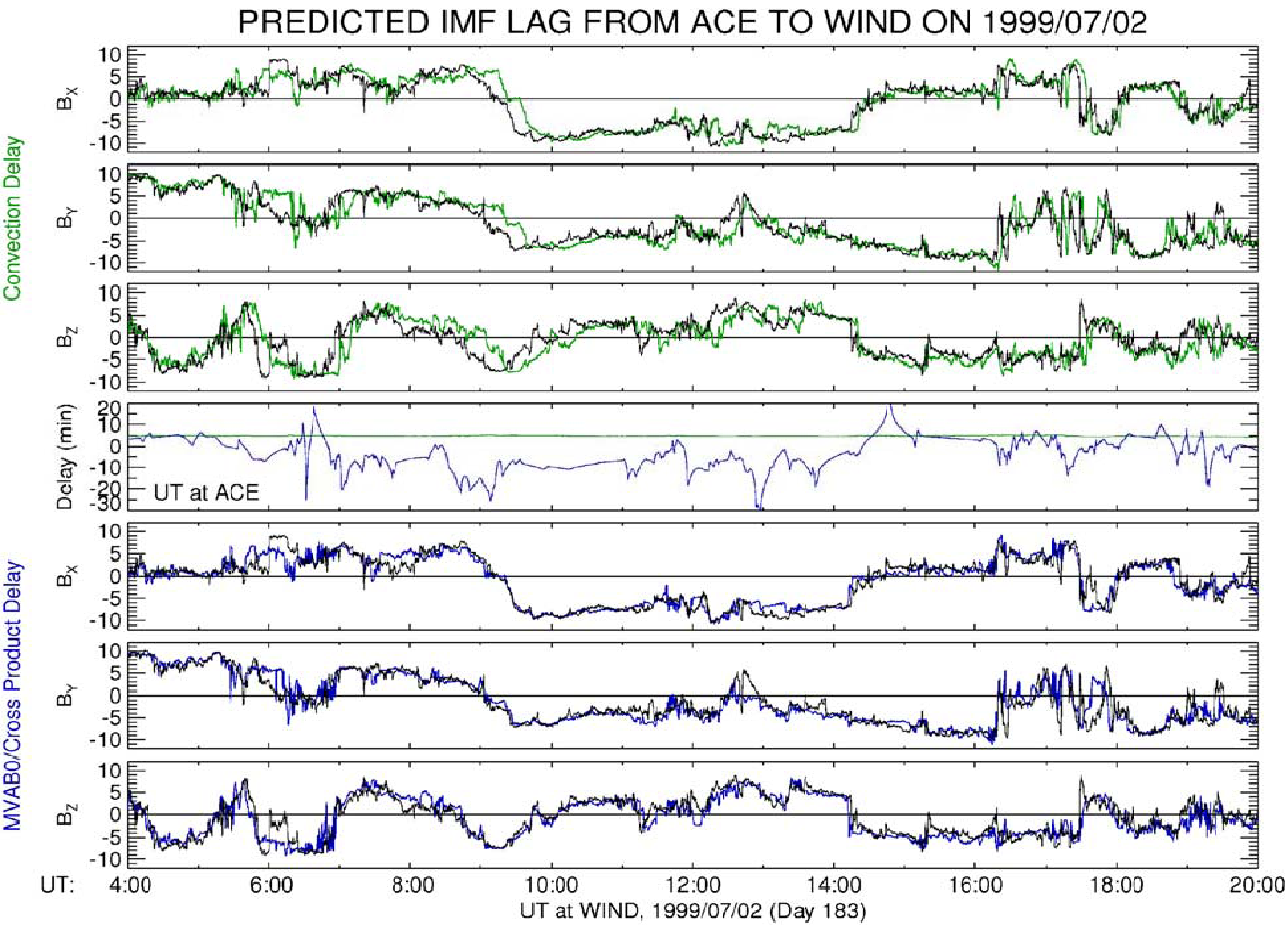
$$\vec{B}_\perp(t_i) = \vec{B}(t_i) - \vec{B}_\parallel(t_i)$$

Direction Cosines of the Normal to Discontinuities



Time Delay by Two Different methods

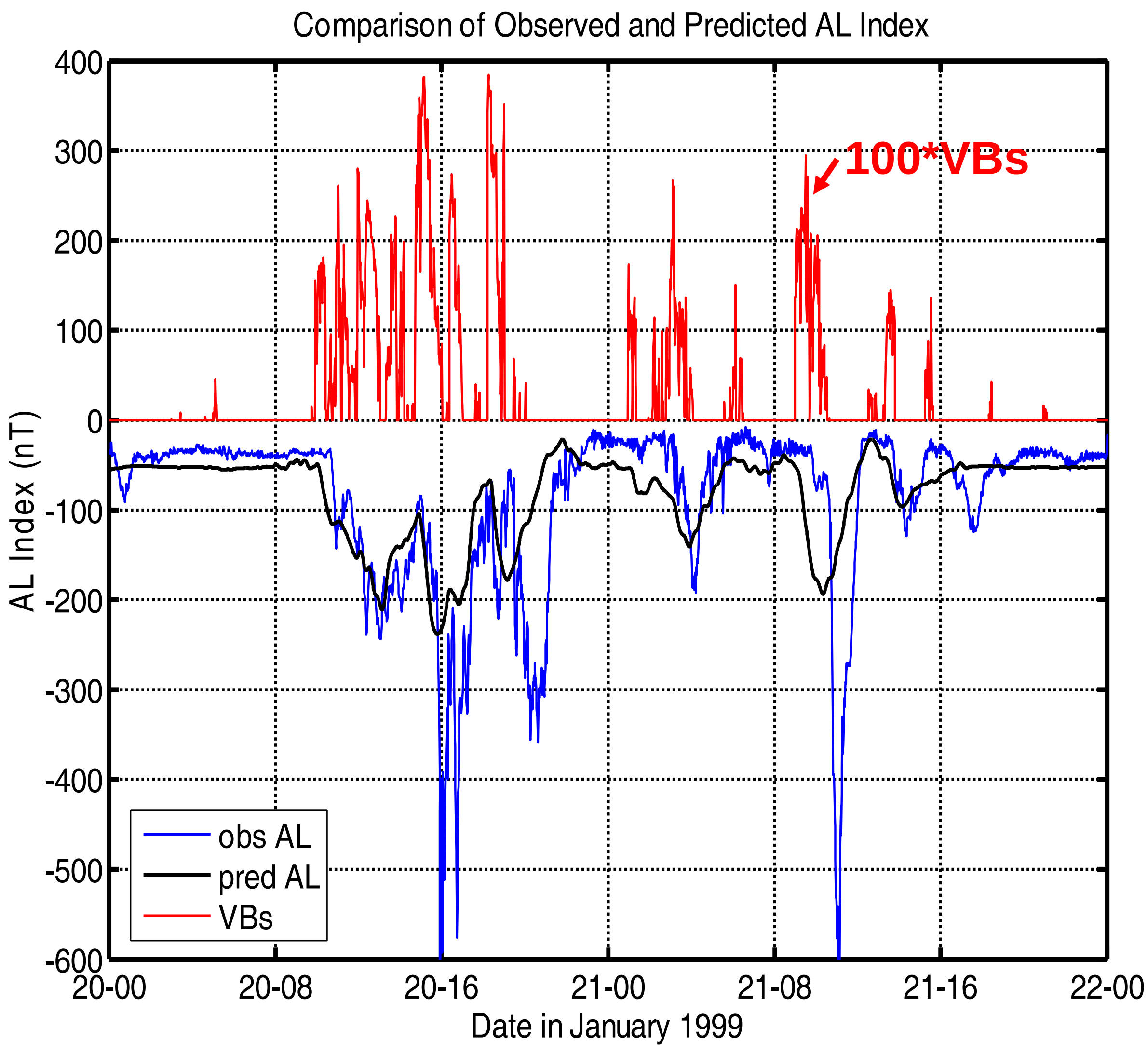




Weimer, D. R., and J. H. King (2008), Improved calculations of interplanetary magnetic field phase front angles and propagation time delays, J. Geophys. Res., 113(A1), 1-14.

Comparison of Prediction with Original

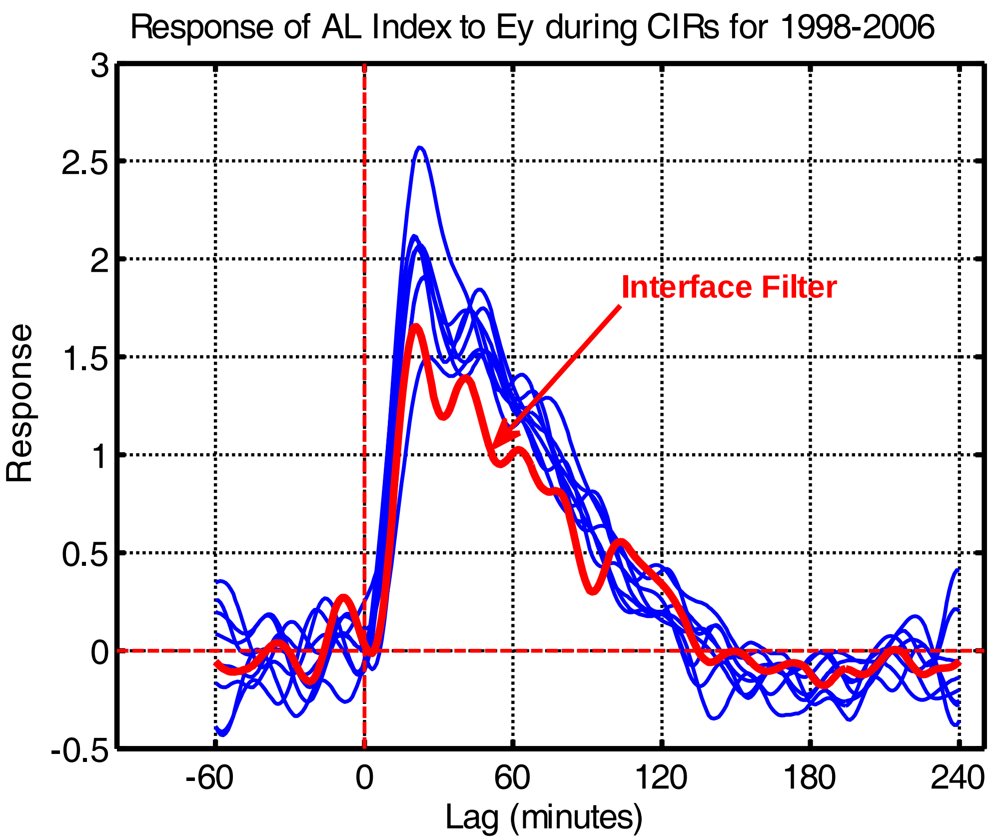
- The IMF driver VB_s is plotted at top in red.
- The original AL index is shown below in blue.
- The linear prediction is shown in black.
- Only the low frequency components of AL are predicted by the low pass filter convolved with the VB_s input time series.



VBs to AL Filters for 1998 to 2006

- Use magnetic field and plasma observations from ACE propagated to bow shock
- Identify all CIR stream interfaces from 1998 to 2006
- Create input and output ensembles with rows for every interface
- For yearly intervals calculate linear prediction filters as function of epoch time

- ***The weakest coupling occurs in the day centered on the interface***

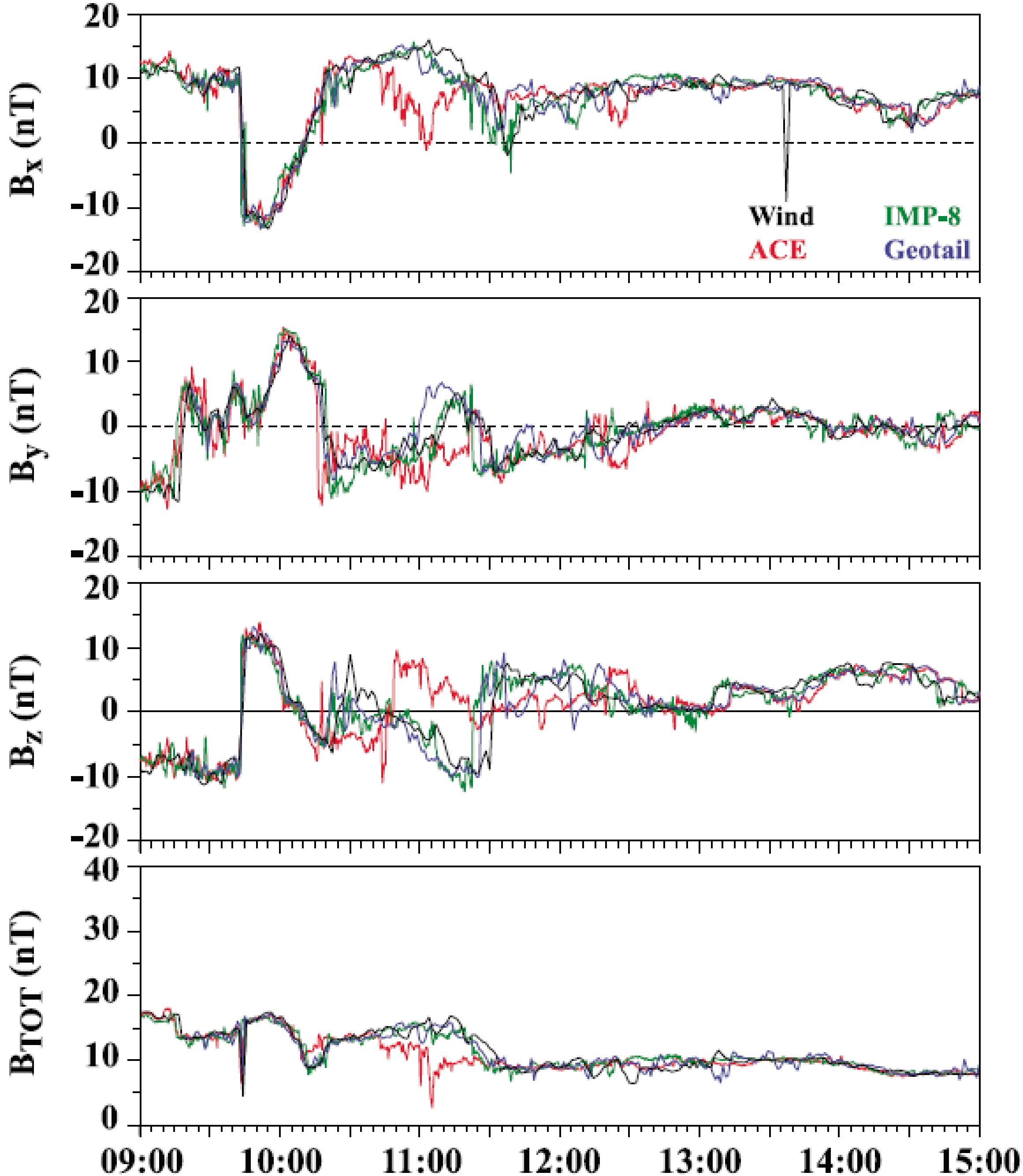


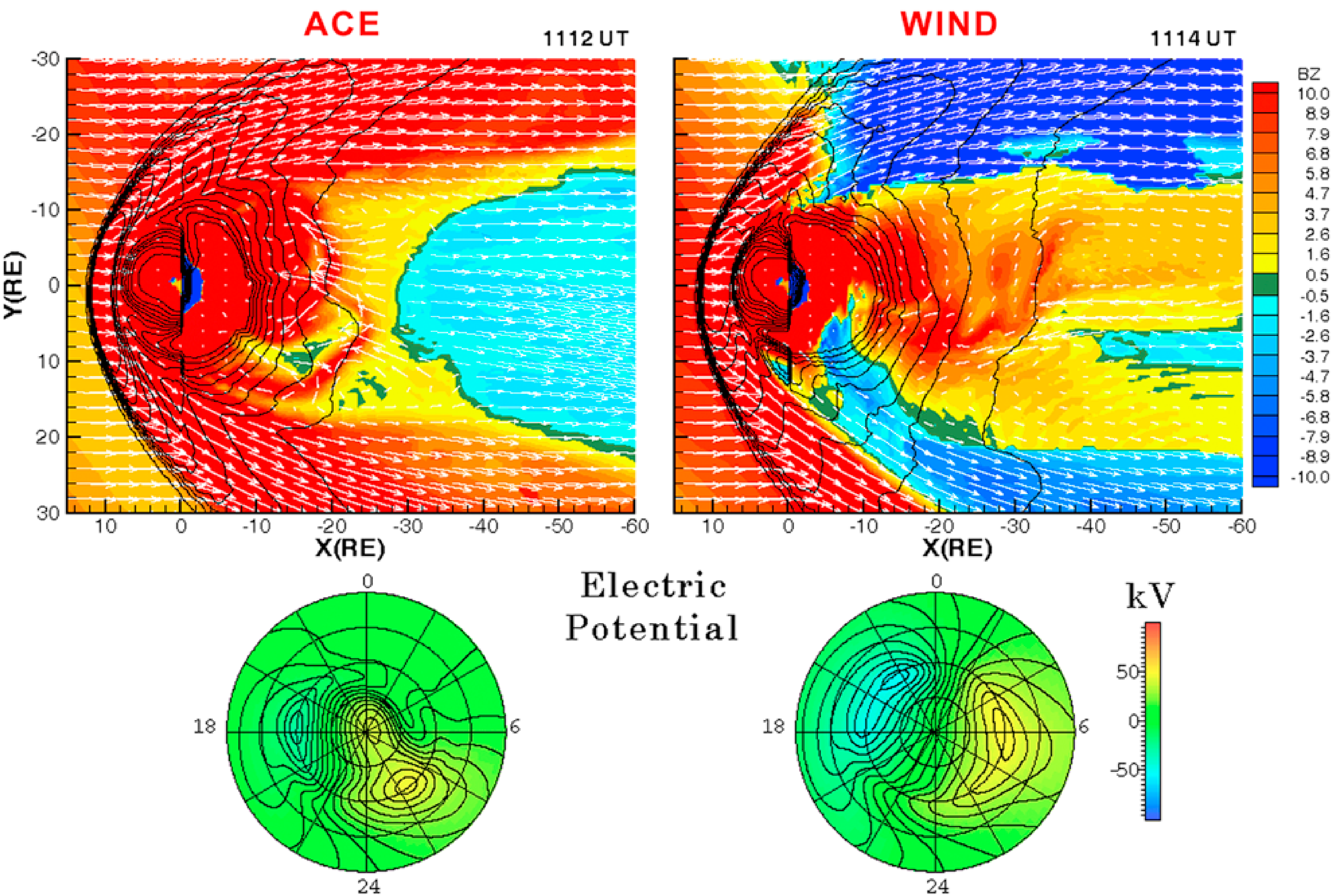
Inadequacies of the L1 to Earth Model

- The current model is based on the assumption that all changes in IMF are produced by tangential discontinuities
- The current model does not have a physical basis for the problem of compression and rarefaction of the solar wind associated with changes in speed
- The current L1 to Earth model fails when the speed is rapidly changing, when the discontinuities in the solar wind are radially aligned, or when the fluctuations orthogonal to mean field are isotropic
- Also the solar wind sometimes contains small scale structures that are observed by one solar wind monitor but not another
- The response of the magnetosphere is very sensitive to differences in the input to models of magnetospheric coupling

Small-scale IMF Structure

- IMF at four spacecraft on May 24, 2000
- Just after 10:30 ACE differs radically from the IMF measured by three other spacecraft closer to the Earth
- We do not expect any model can predict the correct magnetosphere from ACE data in this case





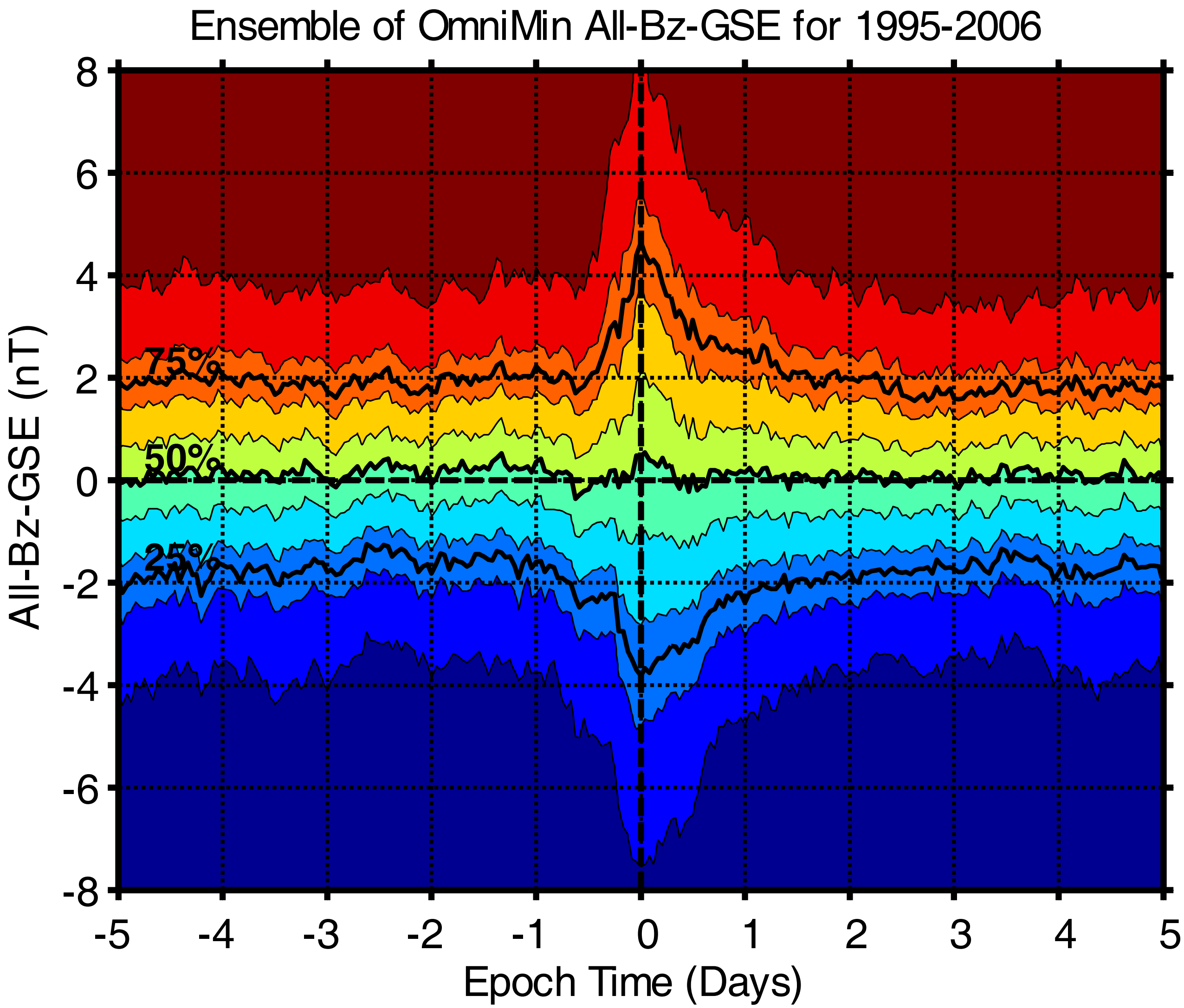
ACE
1112 UT
WIND
1114 UT
Y(RE)
X(RE)
BZ
10.0
8.9
7.9
6.8
5.8
4.7
3.7
2.6
1.6
0.5
-0.5
-1.6
-2.6
-3.7
-4.7
-5.8
-6.8
-7.9
-8.9
-10.0
Electric
Potential
kV
50
0
-50
0
6
18
24

Are the Fluctuations of IMF Predictable?

- The average IMF lies near the solar equatorial plane along the Parker spiral.
- The field fluctuates in all directions about the mean field
- Fluctuations in the geoactive components (Bz & By) are frequent and produced by a variety of causes
- ***It is extremely unlikely any model will ever predict fluctuations of the IMF from observations at the Sun yet these are the cause of geomagnetic activity!***
- Climatology can be used to predict the statistical properties of the solar wind and IMF as a function of time relative to reference times in structures
- Prediction of structure arrival times by empirical or physics-based models and perhaps some properties of the structures can improve the climatology
- ***Generation of surrogate time series from climatology could be used to drive an ensemble of possible inputs to models whose output would provide probabilistic estimates of expected response***

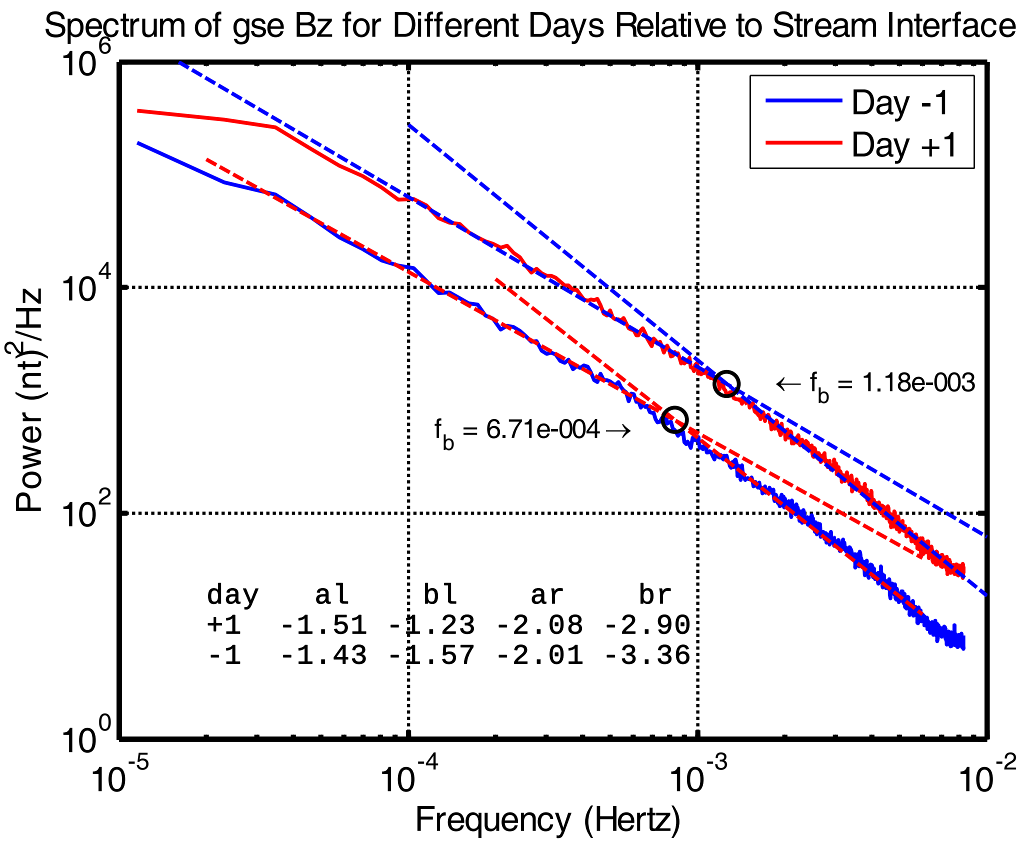
Cumulative Probability of IMF-gse-Bz

- Use 394 CIRs to obtain cdfs of Bz as function of time relative to stream interfaces
- Plot maps of the deciles of the dynamic cdfs
- Fluctuations in Bz are peaked at the interface and are elevated for two days afterwards
- Bz fluctuations after the interface are caused by Alfven waves and are amplified by the high velocity to drive strong activity



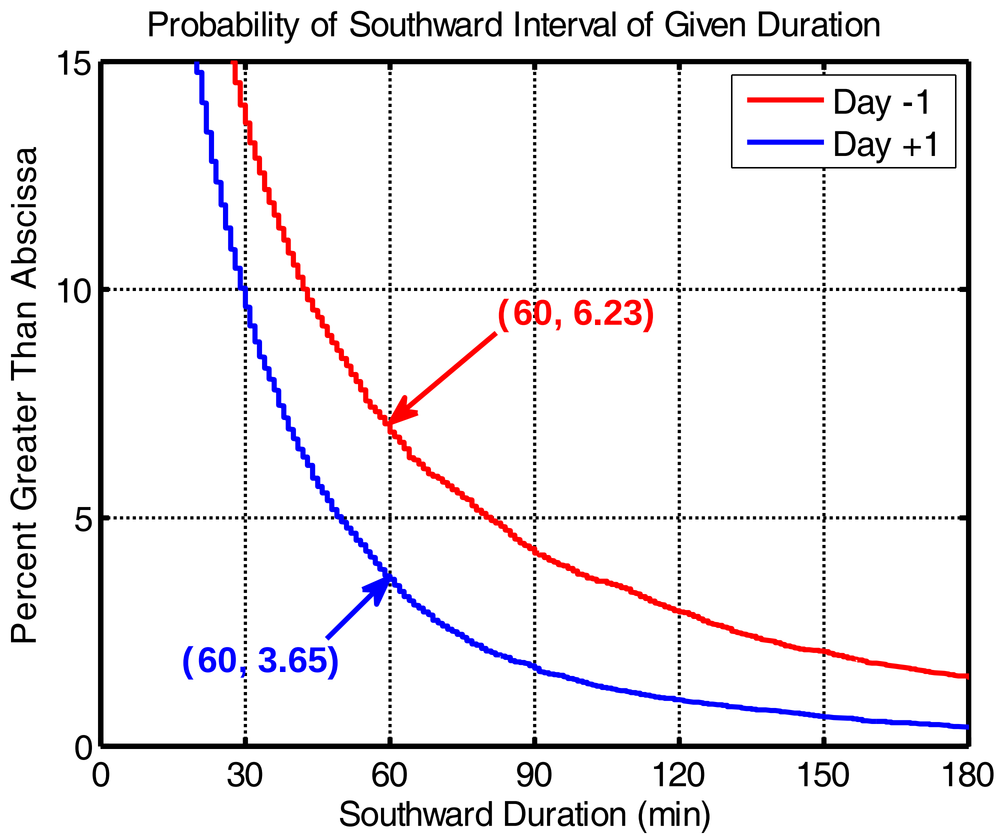
Autospectra of IMF-Bz

- Use 347 stream interfaces from 1995-2007
- Take 24 hours centered on day before and after interface
- Create ensemble average spectra with 694 degrees of freedom per spectral estimate
- Day +1 has three times the power of day -1 and a spectral break at 1.18 mHz as compared to 0.671 mHz



Waiting Time Distribution for IMF Bz

- The waiting time distribution for IMF Bz changes relative to a CIR are shown here
- A list of 394 stream interfaces from 1995-2006 is used to find the probability that an interval of southward field exceeds a certain length
- The distribution one day before (red) a CIR is significantly different than the distribution one day after (blue)
- ***There are almost twice as many intervals of length one hour the day before a CIR than a day after***

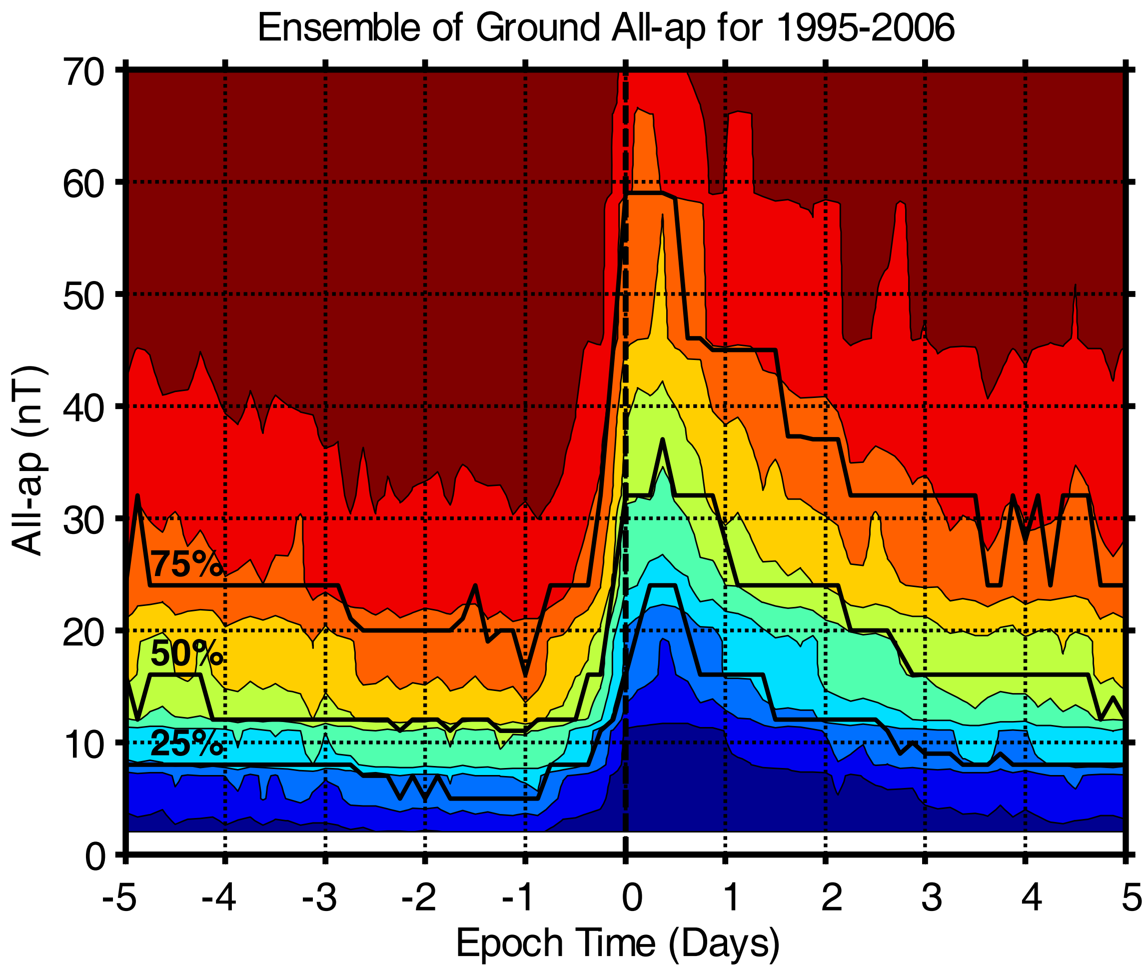


Surrogate Time Series and Probabilistic Forecasting of Space Weather

- A surrogate time series is one generated from random numbers that has a given set of statistical parameters such as probability density function and auto spectrum
- These properties may be defined by climatology, i.e. by an empirical determination of the median and range of values expected at a certain time in the solar wind
- An ensemble of solar wind surrogates can be created and used to drive a magnetospheric model
- The ensemble of outputs can be used to give an estimate of the probability a given parameter will lie in a certain range of values as a function of time

A Probabilistic Forecast of the Ap Index

- The climatology of ap relative to a stream interface is shown by the contour lines in the dynamic cdf
- One day before the interface there is a 50% chance that ap lines in the range 5-20 nT
- One day after the interface the probable range is 15-45 nT



For Forecasting Magnetospheric Physicists Need …

- Significant lead time in predicted properties of wind & IMF
- Arrival times of solar wind structures
  [CIR, CME, HSS, IPS, TD]
- Characteristics of the arriving structures
- One-minute samples of the vector velocity, density, temperature, and composition of the solar wind plasma
- 1-min samples of the IMF vector
- Assurance that the properties predicted at subsolar bow shock are appropriate to entire magnetosphere

The End

Forecasting from Measurements at Sun

- Observations of photospheric magnetic field and structures emitted from Sun
- Conversion of field to boundary conditions of a solar wind model
- Propagation of the observed solar conditions to the Earth's bow shock
- Quantities needed at Earth:
  - Velocity, density, temperature
  - Vector magnetic field
  - Composition (fraction alpha)
- Quantities currently predictable to some degree
  - Speed
  - Field magnitude
  - Field polarity
  - CME and CIR arrival times

An Old Coupling Functions Driving Magnetospheric Activity

- What coupling functions do we use?
  - Dynamic pressure
  - Rectified solar wind electric field or merging electric field
- What does dimensional analysis say?
  - If we are using an energy output as an index of activity we should use an input with the same units

$$p_{dyn} = nMV^2$$

$$E_y = VB_s$$

$$E_m = VB_T \sin^2\left(\theta/2\right)$$

$$E_y = p_{dyn}^{1/6} VB_s$$