Magnetospheric State-Based Modeling and Analysis Tools

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Abstract

Our goal is to **revolutionize** the way space physics data are selected, retrieved, displayed and analyzed, so that space physics and space weather research relevant to the *Living With A Star* (*LWS*) program will be greatly facilitated, and thus will become more efficient and productive. Sun-Earth system science investigations supporting *LWS* have reached a stage where large-scale integration of data and models is essential for gaining further understanding of the inherently multi-scale phenomena. Besides developing good physics-based model formulations, it is essential to have *properly* posed initial and boundary conditions based on appropriate observations to derive good physical solutions to simulation models. Moreover, to obtain physically meaningful solutions, one needs to use data from the same *magnetospheric state* to set up the model.

We have proposed to develop a set of tools that can be used to identify and retrieve, as well as to display and analyze data sets pertaining to a given magnetospheric state. These tools will provide a modeling infrastructure to support *LWS*-relevant space physics research

Introduction

- Due to time-ordering of space physics data, scientifically interesting events must first be identified by their times of occurrence. Using these times,
  - other supportive or ancillary data, e.g., solar wind, interplanetary magnetic field, or geomagnetic indices associated with the event can then be acquired to support event analyses.
  - Time, then, becomes THE most important parameter for selecting, retrieving, and analyzing space physics data.
  - Searching time-ordered data for additional features or events having the same associated geophysical condition, however, is exceedingly tedious, if not impractical.
  - This makes selecting large numbers of events under similar conditions for corroborative or statistical studies difficult.
- We have proposed to develop a set of magnetospheric state-based analysis tools by **linking our newly established *Magnetospheric State Query System* (*MSQS*) to existing space physic data sets so that selection of those data by geophysical conditions or magnetospheric states [*Fung*, 1996; *Fung et al.*, 1999; 2004; *Fung and Shao*, 2004a,b] becomes possible.**

Tools to be Developed

- As examples of our tool applications, we will use our magnetospheric state-based analysis tools to
  - (1) Support selection, retrieval, display and analysis of data sets pertaining to a user-specified geophysical conditions
  - (2) Develop magnetospheric-state based trapped radiation models,
  - (3) Test and validate state-parameter driven empirical magnetic models, such as the Tsyganenko models *[Tsyganenko, 2002* and references therein], and the International Reference Ionosphere (IRI) model.
- **Results from (3) will be provided to model builders for model improvements. Therefore the proposed tools will form the basis of a modeling infrastructure.**

What's Magnetospheric State?

- It may simply refers to the level of "disturbed-ness" of the magnetosphere resulting from conditions imposed by the solar wind and IMF; but…
- A given set of solar wind and IMF conditions can result in a multitude of complex, dynamic magnetospheric phenomena, so the global magnetospheric state should depend on the *combined actions* of solar wind and IMF drivers, as well as the magnetospheric responses to earlier driving conditions.

Magnetospheric State (MS) Specification

- MS may be specified by a MS vector, Ψ
  - $\Psi = \{V_{SW}, \text{IMF}, P_{SW}, \text{F10.7}, K_P, D_{ST}, \text{AE}, \tau\}$

Driver parameters: V_{SW}, IMF, P_{SW}, F10.7

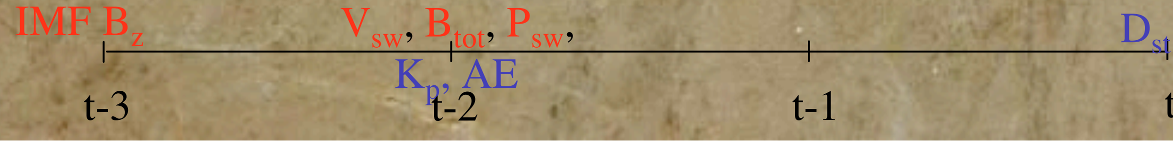
Response parameters: K_P, D_{ST}, AE

Relative time shifts: τ

[Fung, 1996]

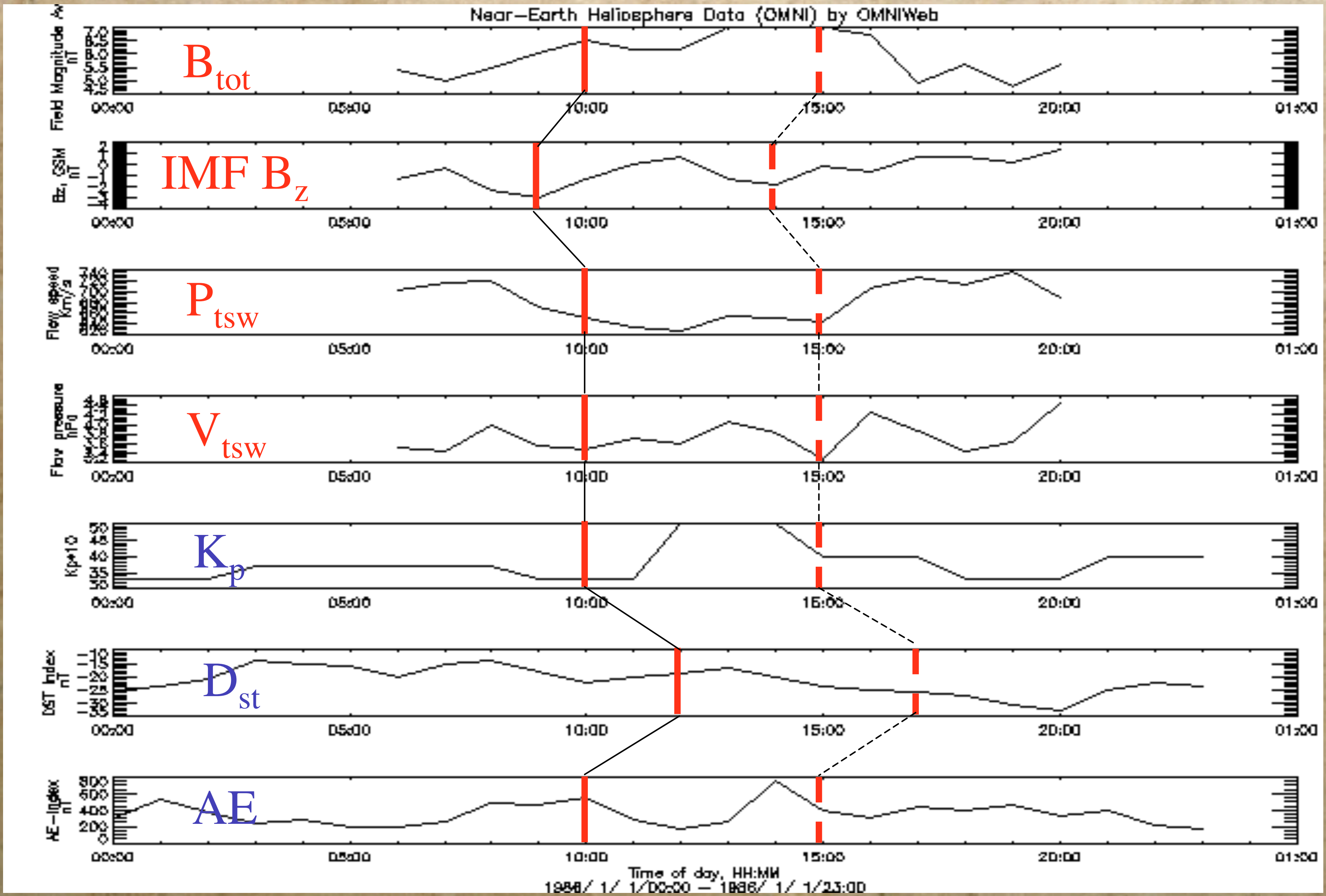
- Optimal relative time shifts have been determined:

Responses \ Drivers	V_{SW}	IMF B_Z	P_{SW}	K_P	AE
K_P	0	0 - 2	0	-	-
D_{ST}	0 - 4	2 - 3	0	2 - 5	1 - 2
AE	0	1	0	-	-



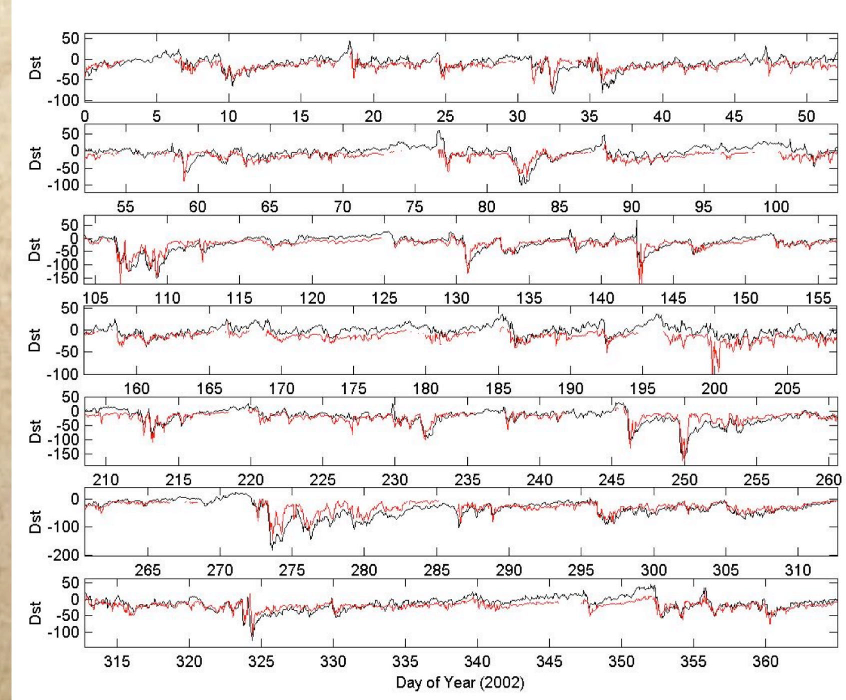
[Fung & Shao, 2004]

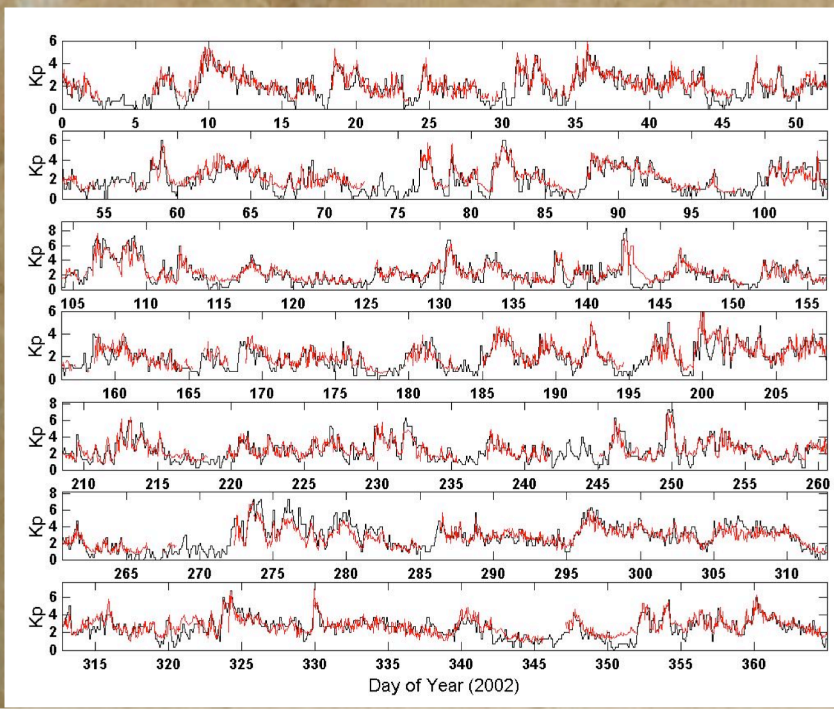
Evolution of Magnetospheric States

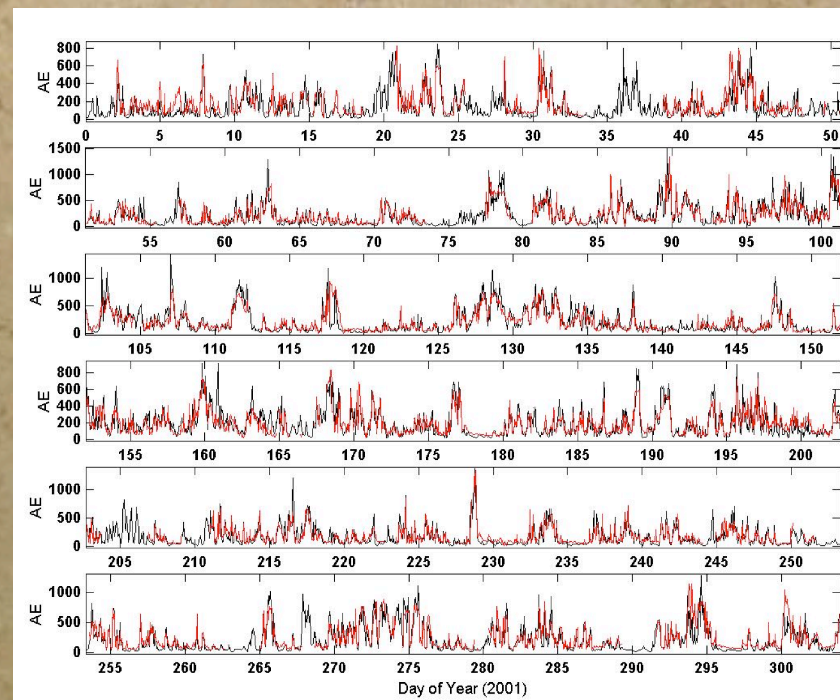


Validation of Magnetospheric States

- Magnetospheric state prescriptions have been determined by using state-parameter data taken in 1970-2000.
- High correlation (r > 0.75) between the prescribed (red traces) and observed (black traces) values of the *multi-time scale* indices: (a) K_P, (b) D_{ST} and (c) AE for the years of 2001 and 2002.
- Gaps in the red traces indicate data gaps in upstream solar wind and/or IMF data.
- Magnetospheric state prescriptions are *model-independent*.







1. Magnetospheric State-Based Data Selection Tool

- We have recently released the first *Magnetospheric State Query System* (*MSQS*)
  - http://radbelts.gsfc.nasa.gov/modeling.html.
- The *MSQS* returns the time intervals when a set of *user-specified* geophysical conditions occurred.
- Time intervals from *MSQS* can be used directly to select, retrieve, and analyze the data for a given magnetospheric state.

The 16 completely selectable state parameters currently in the *MSQS* can be queried with arbitrary time delays and time averages (minimum 1 hour) by a user. This will enable the studying of how multi-time scale physical processes (see Figure 1) may affect the global magnetospheric dynamics, resulting in the changing of magnetospheric states.

Magnetospheric State Query System

Space Physics Data Facility (SPDF)
Goddard Space Flight Center, NASA

Enter Start and Stop Dates: (yyyyddd or yyyymmdd)

Start 19900101 **Stop** 19910101 [Valid Range: (19700101-20030630)]

Solar Activity Parameters:

Parameter	Min	Max	Delay (Hr)	Ave. over (Hr)
R (Sunspot Number)	0	500	0	1
F10.7 Flux	0	500	0	1

Solar Wind Parameters:

Parameter	Min	Max	Delay (Hr)	Ave. over (Hr)
Bx (GSM), nT	-100	100	0	1
By (GSM), nT	-100	100	0	1
Bz (GSM), nT	-100	100	0	1
Bmag (GSM), nT	0	150	0	1
Proton Temp., K	0	1000000(	0	1
Proton Density, /cc	0	200	0	1
Velocity, km/sec	0	2000	0	1
Flow Pressure, nPa	0	100	0	1
Electric Field, mV/m	-100	100	0	1

Geomagnetic Indices:

Parameter	Min	Max	Delay (Hr)	Ave. over (Hr)
Kp	0.0	9.7	0	1
Dst, nT	-1000	100	0	1
AE (hourly), nT	-1000	5000	0	1
AL (hourly), nT	-5000	5000	0	1
AU (hourly), nT	-1000	5000	0	1

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2. Magnetospheric State-Based Trapped Radiaton Modeling

- Magnetospheric state
  - Is a “snapshot” of the global magnetospheric configuration
  - Captures statistically the correspondence between the magetospheric driver and response parameters
- Magnetospheric specification models can be developed for different statistically defined magnetospheric states

Development of Magnetospheric State-Based Trapped Radiation Models

The database for the ith species, $\mathbb{D}_i$

$$\mathbb{D}_i = \{\Psi; \Phi_i\}$$

Where Ψ is the Magnetospheric State Vector

$$\text{e.g., } \Psi = [B_{IMF}, P_{SW}, F10.7; K_P, D_{ST}, AE, AL; \boldsymbol{\tau}]$$

Drivers — Multi-scale Responses — Time delays

and Φ_i is the set of energetic particle data files,

$$\Phi_i = \{\phi_1, \phi_2, \phi_3, \ldots \phi_N\}$$

with each ϕ_n being associated with a given Ψ_n. Thus for

$\Psi = \Psi_o$, we may write $\phi = \phi_o$

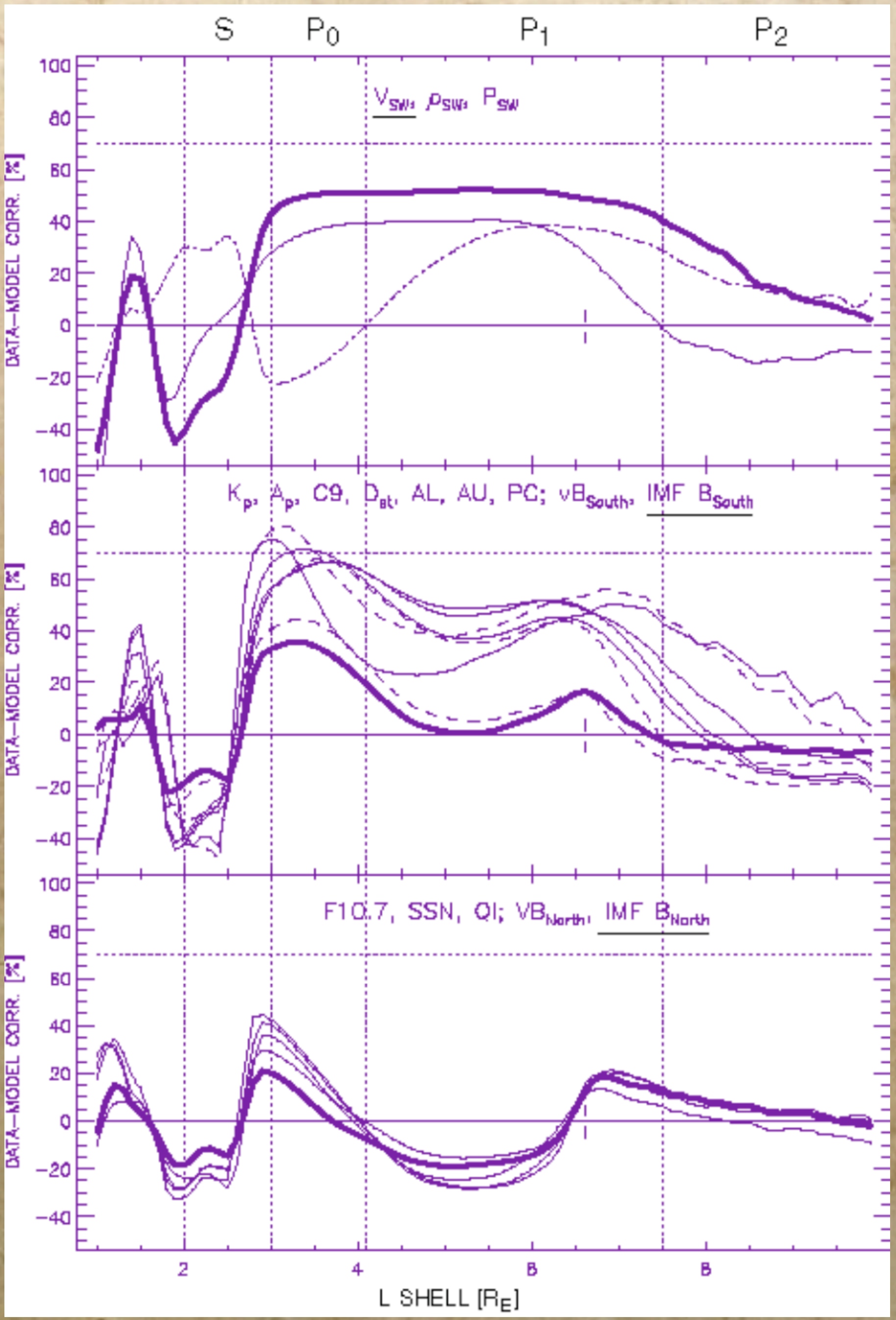
$$\phi_o = [R; B/B_o, L; E, \alpha, J_\alpha, J_{OMN}]$$

[see Fung, 1996]

Multi-Parameter Specification of Radiation Belts

Vassiliadis, Fung and Klimas [2004] showed:

- Different magnetospheric-state parameters "affect" different parts of the radiation belt differently
- Correlations between observed fluxes and FIR-modeled fluxes driven by different MS parameters indicate different relativistic electron production regions/processes
- Multiple parameters are therefore needed to specify the state the radiation belts



Magnetic Coordinates [B/B$_{min}$, L$_{McIlwain}$] Are Magnetic Field Model-Dependent

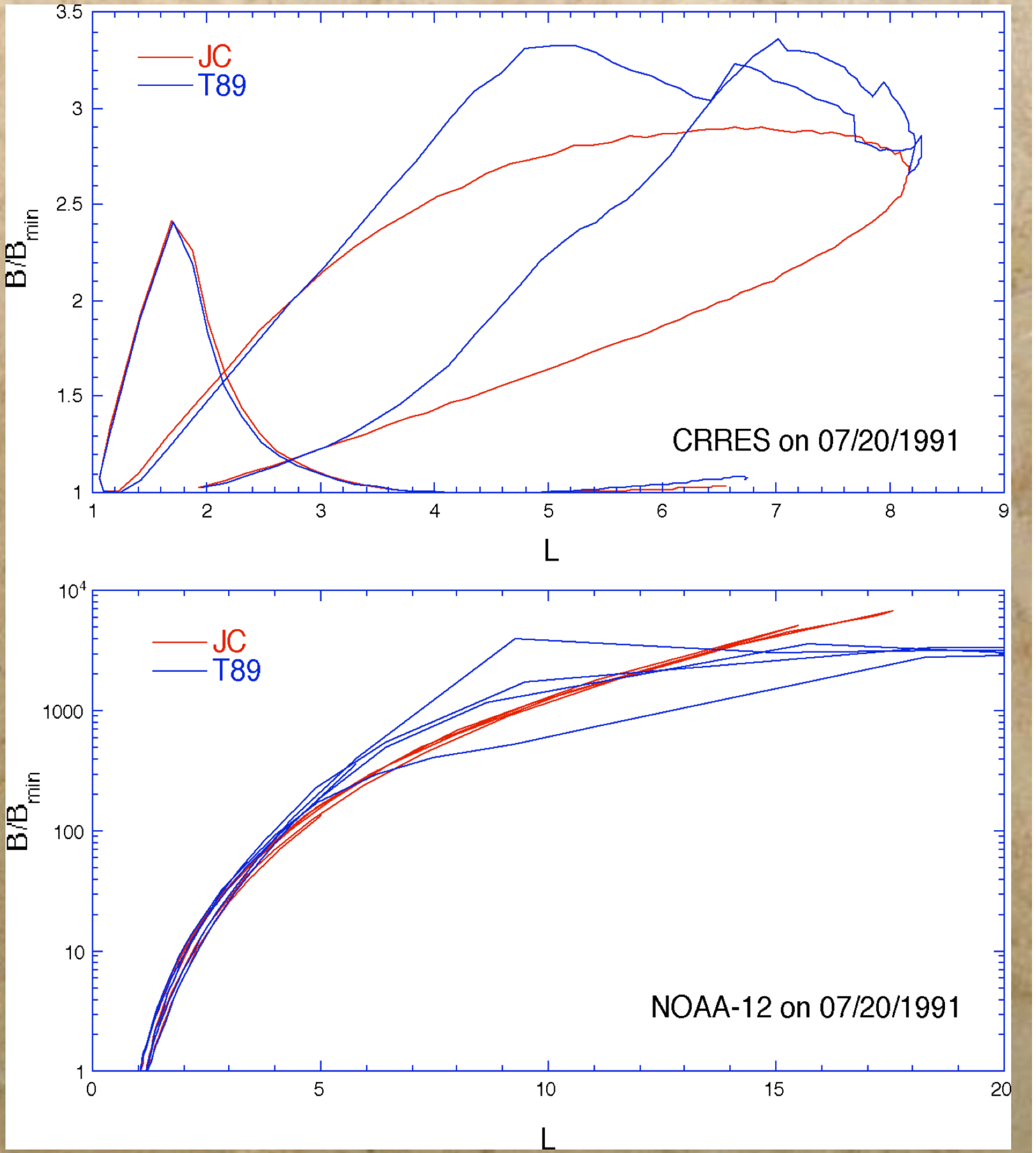
Upper panel

- CRRES satellite positions (07/20/1991 at 00:00-15:00 UT) based on Jensen & Cain (red trace) and IGRF+Tsyganenko 89 model (blue trace)

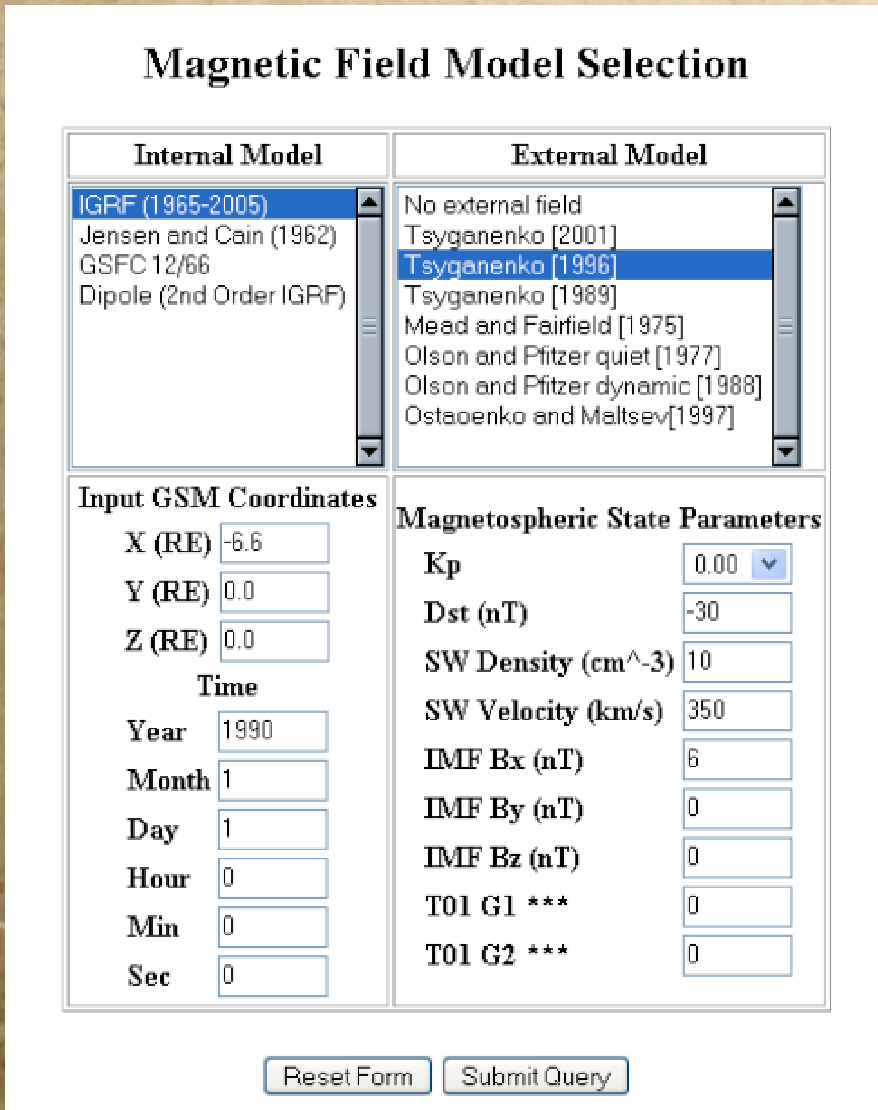
Lower panel

- NOAA-12 satellite positions at 00:00-02:00 UT

A single magnetic field model should be used to process all data used in a given modeling analysis.



Changing Magnetic Field Models



Magnetic Field Model Selection

Internal Model	External Model
IGRF (1965-2005) Jensen and Cain (1962) GSFC 12/66 Dipole (2nd Order IGRF)	No external field Tsyganenko [2001] Tsyganenko [1996] Tsyganenko [1989] Mead and Fairfield [1975] Olson and Pfitzer quiet [1977] Olson and Pfitzer dynamic [1988] Ostaoenko and Maltsev[1997]

Input GSM Coordinates		Magnetospheric State Parameters	
X (RE)	-6.6	Kp	0.00
Y (RE)	0.0	Dst (nT)	-30
Z (RE)	0.0	SW Density (cm^-3)	10
Time		SW Velocity (km/s)	350
Year	1990	IMF Bx (nT)	6
Month	1	IMF By (nT)	0
Day	1	IMF Bz (nT)	0
Hour	0	T01 G1 ***	0
Min	0	T01 G2 ***	0
Sec	0		

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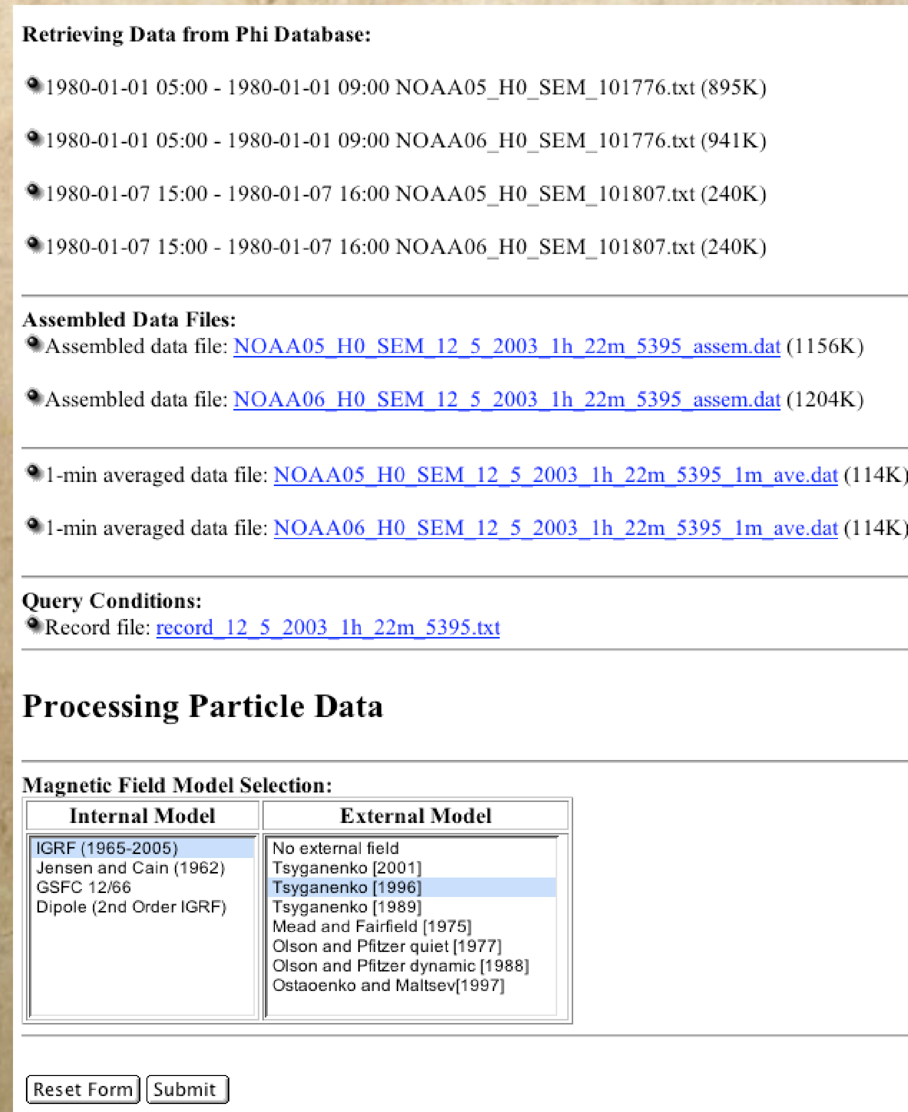


Retrieving Data from Phi Database:

- 1980-01-01 05:00 - 1980-01-01 09:00 NOAA05_H0_SEM_101776.txt (895K)
- 1980-01-01 05:00 - 1980-01-01 09:00 NOAA06_H0_SEM_101776.txt (941K)
- 1980-01-07 15:00 - 1980-01-07 16:00 NOAA05_H0_SEM_101807.txt (240K)
- 1980-01-07 15:00 - 1980-01-07 16:00 NOAA06_H0_SEM_101807.txt (240K)

Assembled Data Files:

- Assembled data file: NOAA05_H0_SEM_12_5_2003_1h_22m_5395_assem.dat (1156K)
- Assembled data file: NOAA06_H0_SEM_12_5_2003_1h_22m_5395_assem.dat (1204K)

- 1-min averaged data file: NOAA05_H0_SEM_12_5_2003_1h_22m_5395_1m_ave.dat (114K)
- 1-min averaged data file: NOAA06_H0_SEM_12_5_2003_1h_22m_5395_1m_ave.dat (114K)

Query Conditions:

- Record file: record_12_5_2003_1h_22m_5395.txt

Processing Particle Data

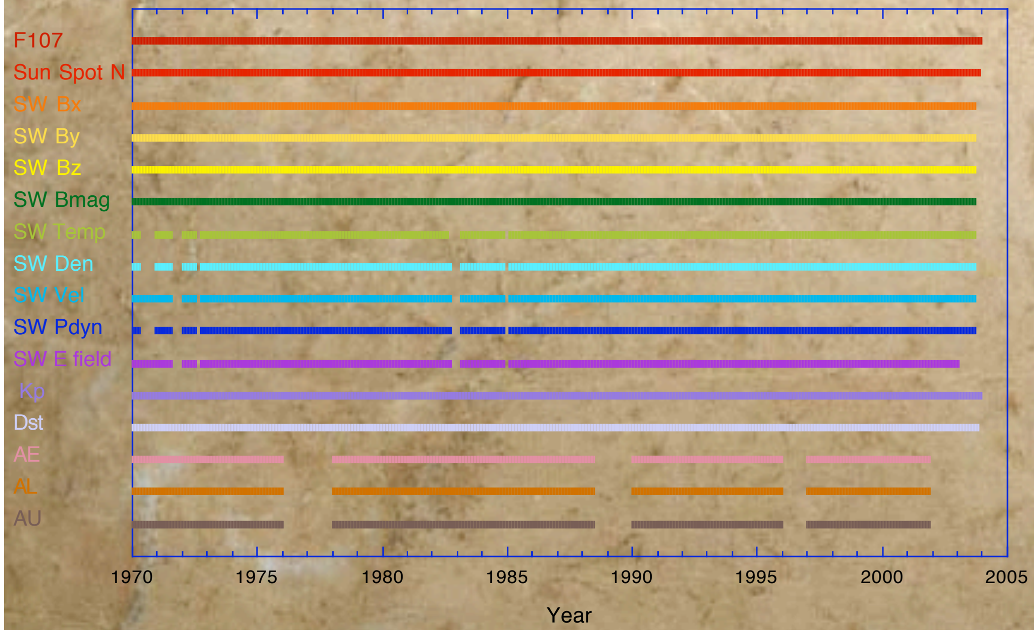
Magnetic Field Model Selection:

Internal Model	External Model
IGRF (1965-2005) Jensen and Cain (1962) GSFC 12/66 Dipole (2nd Order IGRF)	No external field Tsyganenko [2001] Tsyganenko [1996] Tsyganenko [1989] Mead and Fairfield [1975] Olson and Pfitzer quiet [1977] Olson and Pfitzer dynamic [1988] Ostaoenko and Maltsev[1997]

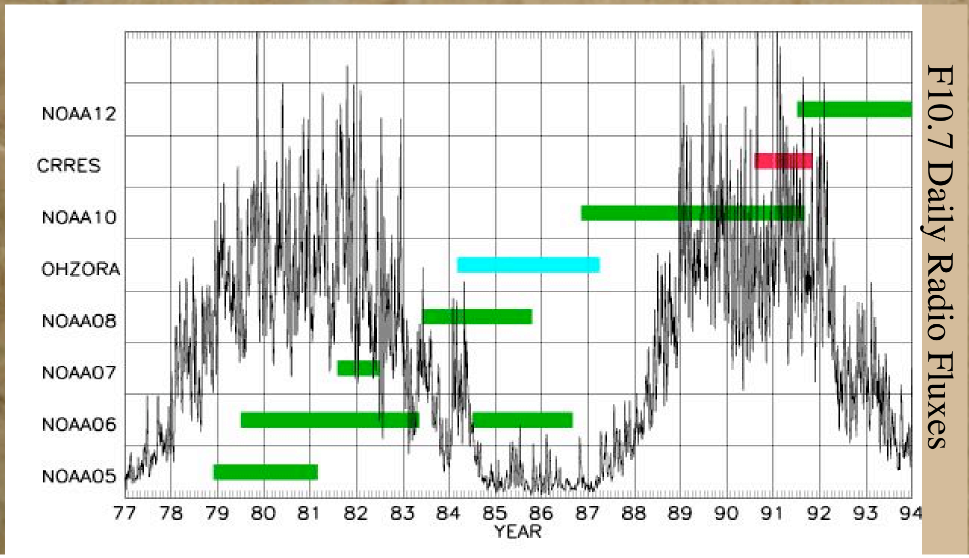
Reset Form | Submit

- A McIlwain magnetic coordinate calculator has been constructed to compute the [B/B_0, L] coordinates of any spatial point based on a *user-specified* magnetic field model and Y conditions
- The calculator is being adapted to re-process different F (particle) data sets, which may have been processed originally with different field models.

Prototype [Ψ, Φ] Database Data Coverage and Field Model Options



- Ψ and Φ data cover more than one solar cycle
- Initial low-altitude satellite data are suitable for low-altitude modeling



Internal Magnetic field Model	External Magnetic Field Model
IGRF	Mead and Fairfield
Jensen & Cain	Olson and Pfitzer quiet
GSFC 12/66	Olson and Pfitzer dynamic
Centered Dipole	Ostapenko &Maltsev
	Tsyganenko 1989c
	Tsyganenko 1996
	Tsyganenko 2001

Particle (Φ) Data Processing

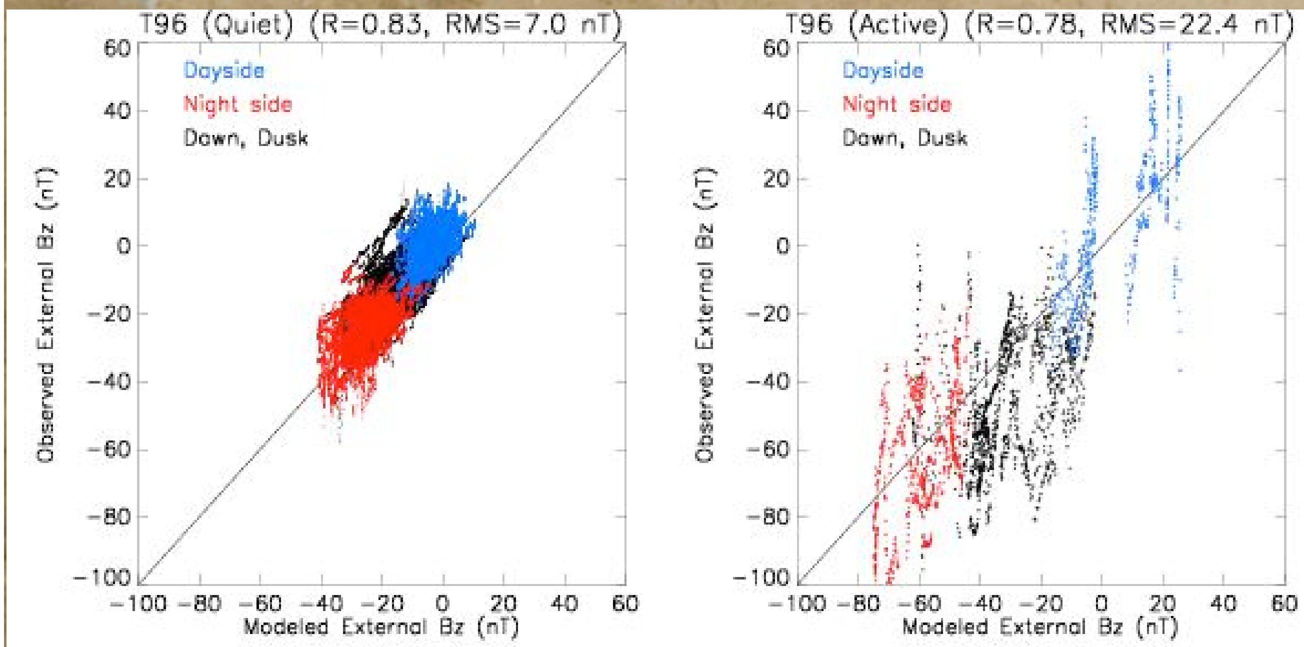
- Particle data sets need to be processed & put into the Φ database
- Raw measurements are processed into 1-min particle data records
- Each time record contains $\Phi_0 = [\mathbf{R}; B/B_o, L; \mathrm{E}, \alpha, J_\alpha, J_{omn}]$
- NOAA satellite data, for examples
  - R = [Lat, Long, Alt]
  - Compute [B, L] = $[(B_X, B_Y, B_Z)_{GSM}, L_{McIlwain}]$ and B_O
    - based on IGRF, T89, T96, T01
  - Trapped particles, $J_a = J_\perp \ sin^N a$
    - For electrons (> 0.03, > 0.1, > 0.3 MeV)
      - N, $J_\perp$, and J_{OMN} @ L < 2
      - For N = 5, $J_\perp$, and J_{OMN} @ $L > 2$
    - For protons (30-80, 80-250, 250-800, >2500 keV)
      - N, $J_\perp$, and J_{OMN} @ L < 2 (no data at L > 2)
  - Protons J_{OMN} @ E (MeV) > 0.03, > 0.08, > 0.25, > 0.8, > 2.5, > 16, > 36, > 38

3. Validation of Global Magnetospheric Models

- Global Magnetospheric Field Model
  - Empirical global magnetic field models, e.g. Tsyganenko models (T89, T96, T01) [*Tsyganenko*, 1989,1996, 2002], using observations independent of those used in constructing the models.

Quiet conditions:
SW Pdyn < 1 nPa, IMF Bz > 0 nT, and Dst > -20 nT

Active conditions:
SW Pdyn > 5 nPa, IMF Bz < 0 nT, and Dst < -60 nT



- It is feasible to test magnetic field models [e.g., T96] with magnetic field observations pertaining to different magnetospheric states
- For example, geosynchronous GOES-9 observations during different MS conditions in 1995-1998 can be selected using the *MSQS* and compared with T96.
- Correlation coefficient (R) and root-mean-squared error (RMS) between model and observation are shown on top of each panel.

- International Reference Ionosphere (IRI) Model
  - The IRI model drivers are the sunspot number, the ionospheric index IG (based on ionsonde *F*-peak measurements), and the A_p-storm index.
  - these indices will be added to *MSQS* and thus will allow testing of the IRI algorithms against the ITM satellite observations.
  - time-averaging capabilities of *MSQS* will help find the optimal averaging periods for getting good correlation between ionospheric parameters and solar (SSN)/ionospheric indices.

Summary

- A set of *magnetospheric state-based modeling and analysis* tools is proposed
- As described above, such tools will support:
  - Searching, selecting, retrieving and analysis of space physics datasets pertaining to *user-specified* solar wind *and* magnetospheric conditions
    - Magnetospheric State Query System (*MSQS*) already developed
  - Validating and improving existing space physics models
    - e.g., Global magnetic field (empirical or MHD) and IRI models
    - Discrepancies found through data-model comparisons for *given conditions* will help guide future modeling efforts
  - Constructing new magnetospheric specification models
    - e.g., New-generation trapped radiation models [*Fung*, 1996]
  - The proposed tools and models can become part of the LWS virtual observatory (VO) infrastructure to support
    - LWS-relevant research to gain understanding of Sun-Earth system (e.g., ionospheric storm effects)
    - Space environment weather modeling for nowcasting and forecating