Chandra Radiation Environment Modeling

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Overview

- Introduction – Chandra and ACIS radiation issue
- Chandra Radiation Model (CRMFLX) development and implementation
- Model results
- Summary

- Acknowledgements:
  - Geotail/EPIC Data: Richard McIntire, Stuart Nylund (JHU/APL)
  - Polar/IPS Data: Harlan Spence, James Sullivan (Boston University)
  - CXO Ephemeris: Tom Guffin, Bill Davis, Bill Cooke, Steve Smith (CSC)
  - Geotail/CPI Data: Louis Frank, William Patterson (University of Iowa)

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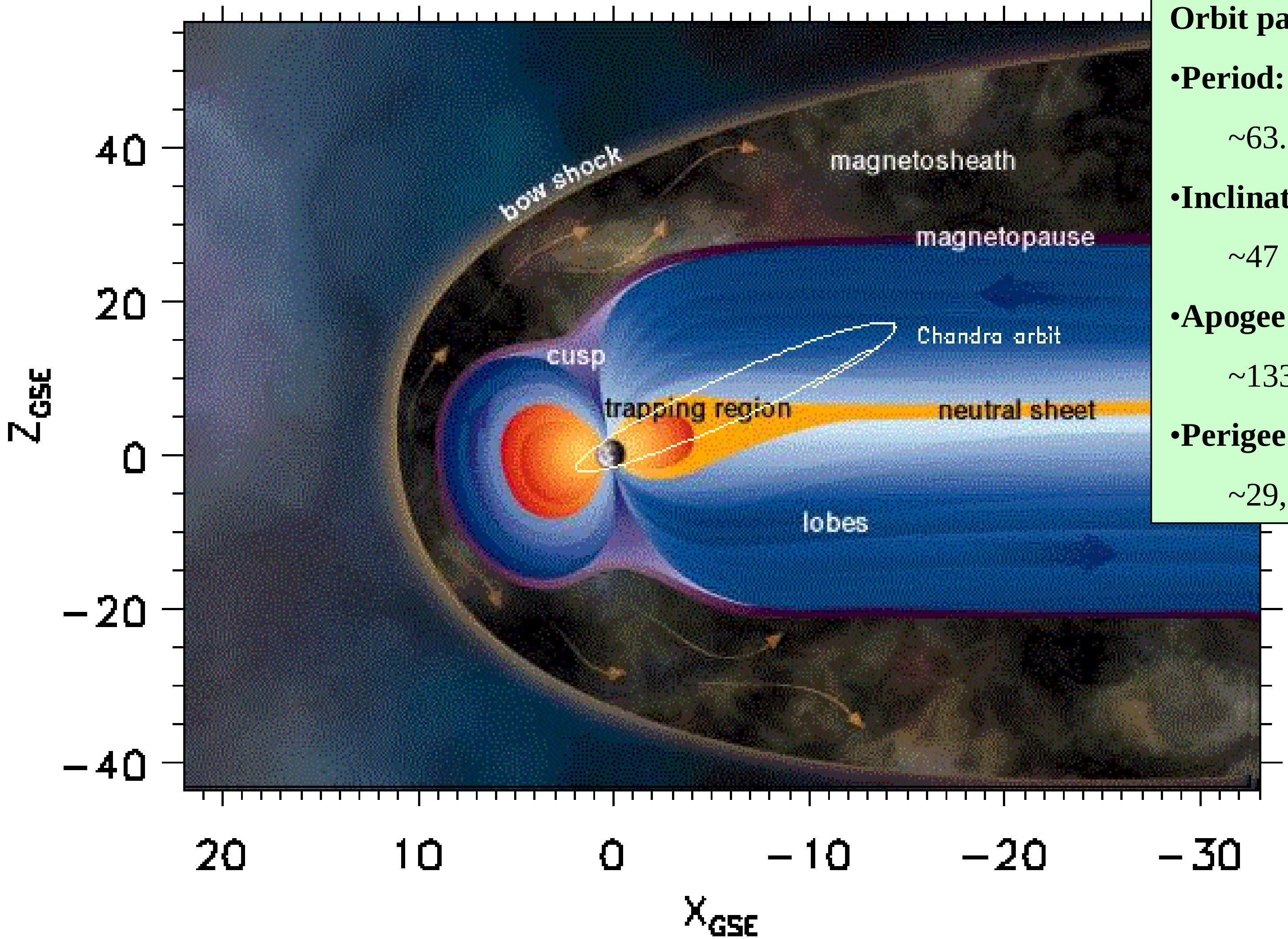
Chandra Orbit



Orbit parameters (Jan 2003)

- **Period:**
  - ~63.5 hours (2.6 days)
- **Inclination:**
  - ~47 degrees
- **Apogee:**
  - ~133,000 km (20.8 R_e)
- **Perigee:**
  - ~29,000 km (4.5 R_e)

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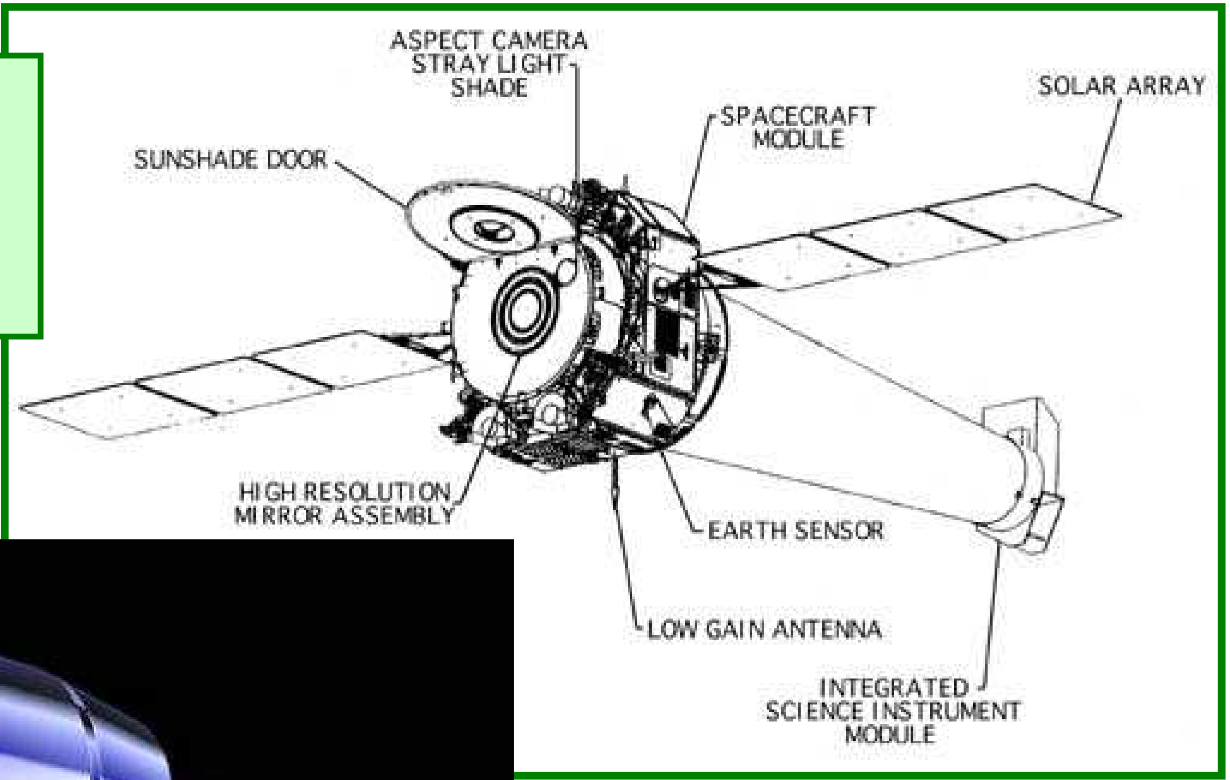
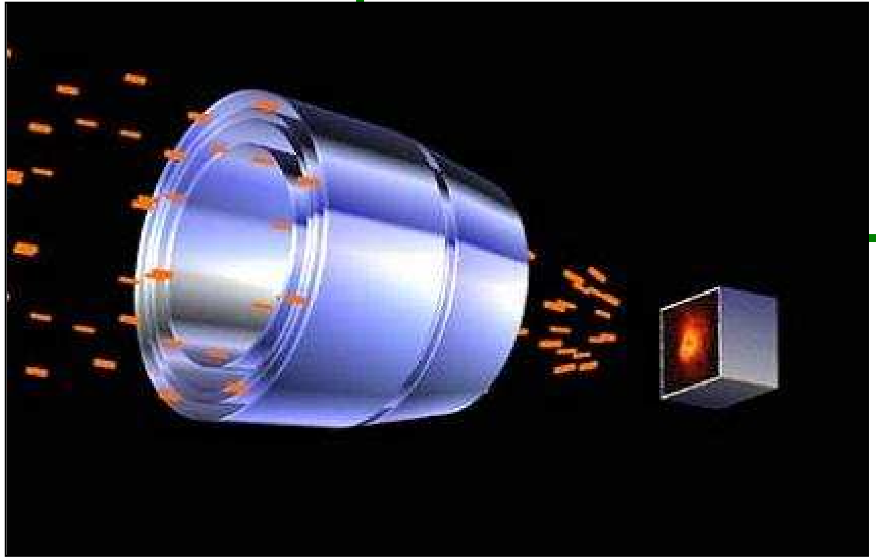
Chandra X-Ray Observatory (CXO)

X-ray optics require grazing incidence mirrors to scatter photons onto detectors





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Chandra ACIS Radiation Issue

- **Advanced CCD Imaging Spectrometer (ACIS) detector is sensitive to radiation degradation while inside the magnetosphere**
  - Grazing incidence mirrors also scatter ions onto detector arrays
- **100 - 200 keV protons produce damage sites in CCD material**
  - E < 100 keV can't penetrate filter, CCD material
  - E > 200 keV pass through sensitive region of CCD with little interaction.
  - Ring current ion flux peaks in the 100-200 keV energy range, ions of this energy are very common during geomagnetic storms.
- **Radiation damage of front-illuminated (FI) CCDs produces a measurable increase in the charge transfer inefficiency (CTI) due to electron trapping at ion displacement damage sites**
  - 8 of 10 CCDs in ACIS array are FI-CCD.
  - ACIS is moved from the focal plane to a shielded position during radiation belt passages.
  - CXO program must carefully schedule ACIS operations to minimize degradation but maximize science observation time
  - ACIS is the premier science instrument on Chandra….loss of science time!!

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Ion Flux Model

- **Mitigation of FI-CCD sensor degradation and scheduling of ACIS observations required a low energy proton environment model:**
  - Protons 100-200 keV
  - Outer magnetosphere (ACIS will never be used inside geostationary orbit)
  - Magnetosheath and solar wind flux
  - Model must provide asymmetric dawn-dusk flux distributions
  - Statistical ion flux estimates at 50%, 95%, other program selected levels
  - Computationally efficient model for trade studies in scheduling on-orbit events
  - Events must be scheduled 3+ weeks in advance
- **CRMFLX approach:**
  - Empirical engineering model of the free field outer magnetosphere, magnetosheath, and solar wind 100-200 keV proton flux
  - Flux statistics from database of satellite measurements
  - Easily incorporates data from multiple satellites

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Database

Geotail EPIC/ICS (1995-current)

Channel	Energy (keV/e)	Time Res (sec) original[a]	Time Res (sec) database[b]
P2	58.1 - 77.3	6	288
P3	77.3 - 107.4	48	288
P4	107.4 - 154.3	48	288
P5	154.3 - 227.5	48	288
P6	227.5 - 341.6	48	288
P7	341.6 - 522.5	48	288
P8	522.5 - 813.5	48	288
P9	813.5 - 1560.8	96	288
P10	560.8 - 3005.4	96	288

[a]Temporal resolution of EPIC flux measurements.
[b] Temporal resolution of spin average flux provided by JHU/APL.

Polar CEPPAD/IPS (1996-current)

Channel	Energy Thresholds (keV)			
	Set 1		Set 2	
	Min	Mid	Min	Mid
0	16.8	18.9	13.9	15.6
1	21.2	24.4	17.5	19.9
2	27.9	32.4	22.6	26.2
3	37.5	43.1	30.3	35.4
4	49.6	57.2	41.4	48.1
5	65.9	76.0	55.9	55.2
6	87.7	102.0	75.9	88.4
7	118.0	138.0	103.0	121.0
8	161.0	188.0	142.0	168.0
9	221.0	259.0	198.0	234.0
10	303.0	355.0	277.0	327.0
11	417.0	489.0	387.0	459.0
12	574.0	674.0	543.0	643.0
13	791.0	929.0	762.0	903.0
14	1091.0	1281.0	1071.0	1269.0
15	1505.0	2000.0	1505.0	2000.0

Time resolution is 96 seconds for all channels.

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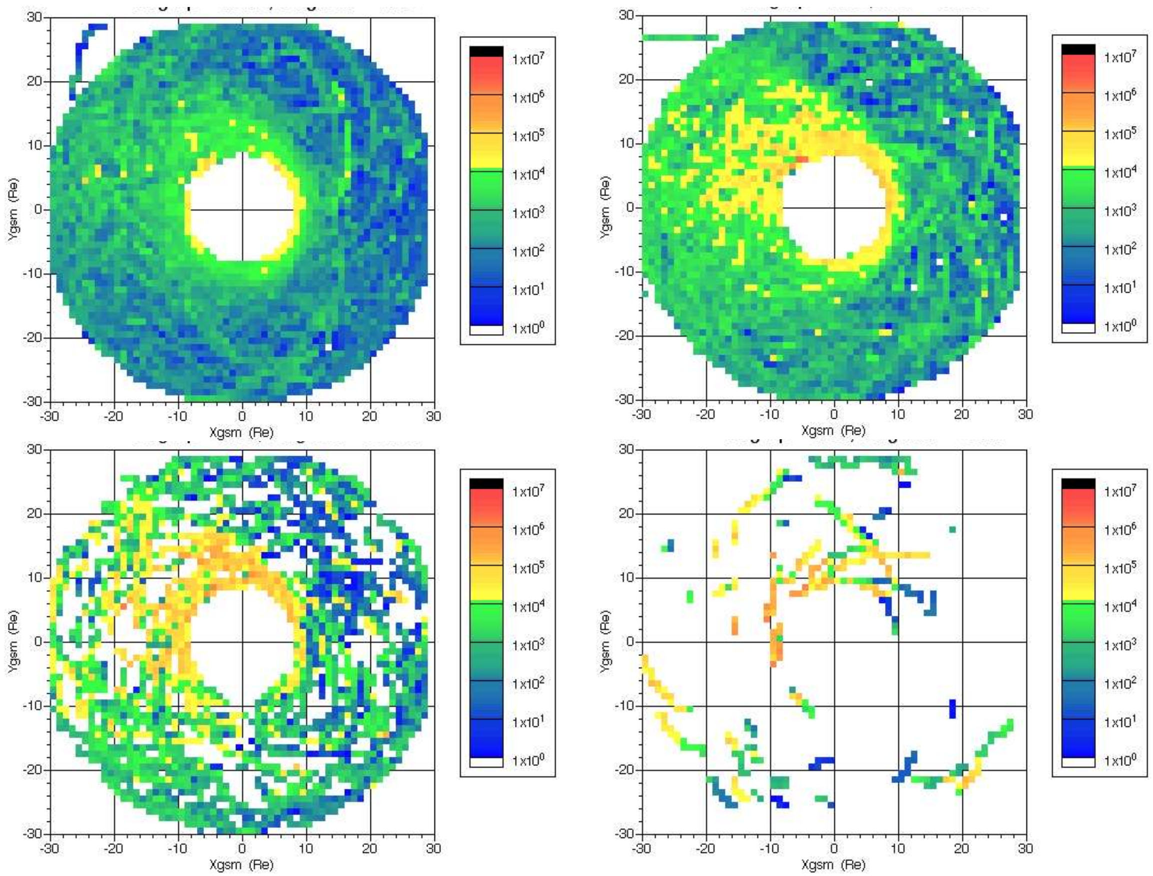
CRMFLX 1 Proton Flux Database

Geotail data projected onto Z=0 plane
No flux mapping

Kp 0-2

Kp 2-4



Kp 4-6

Kp 6-9

Poor flux statistics
at high Kp!

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CRMFLX Version 1

- **Database**
  - GSM coordinates provides magnetosphere aligned system for estimates of seasonal, diurnal variations in ion flux along CXO orbit
  - Geotail/EPIC observations 1 January 1995 through 30 April 2000
  - Plasma regime identification at ~1 hr resolution using Univ. of Iowa on-line CPI/HPA survey plots.
- **Simple empirical model using XYZ volumetric regions**
  - Flux binned in 3-D Cartesian GSM grid
  - Average flux pre-calculated for each bin to yield run-time database
  - Multiple databases for varying Kp levels
- **Nearest-neighbor approach used to derive flux at spacecraft location**
  - Flux only available at (data) observation points…no mapping of data
    - Flux at Chandra location interpolated from database
  - Interpolation never implemented across plasma regions (e.g., 'sheath never mixed with 'sphere)
    - Constraints placed on near-neighbor choice
- **Model provides estimate of flux, average fluence per orbit**
  - Fluence levels can be estimated for different safing strategies

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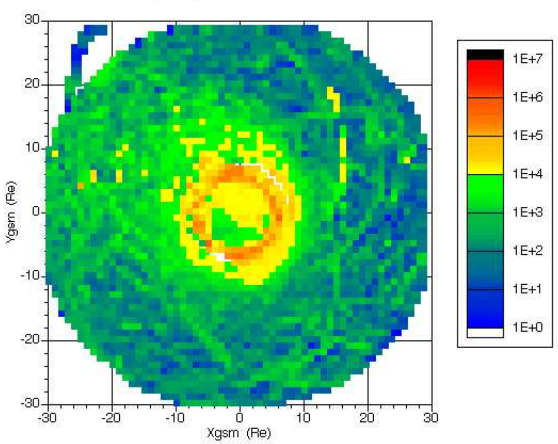
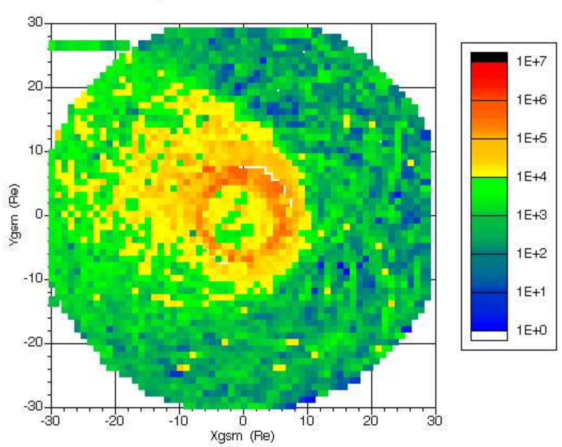
CRMFLX 2 Proton Flux Database

Geotail, Polar data projected onto Z=0 plane
No flux mapping

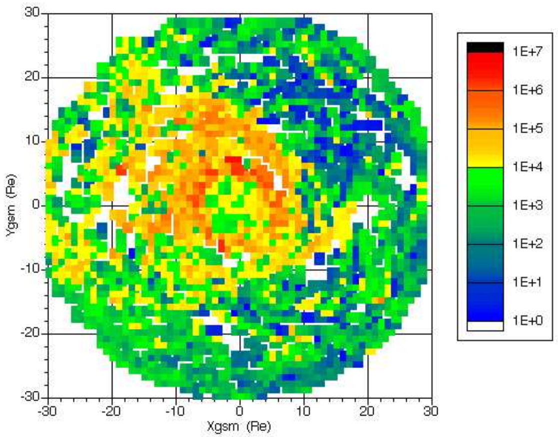
Kp 0-2



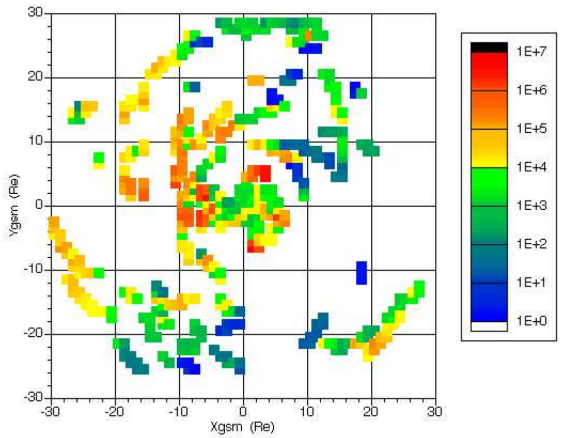
Kp 2-4



Kp 4-6



Kp 6-9



Poor flux statistics at high Kp!

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New Features in CRMFLX Version 2

- **Flux mapping to more completely fill out the database**
  - **ExB, ∇B, curvature drifts used to compute ion drifts**
  - **Fills in spatial gaps in database**
  - **Provides better flux predictions at high magnetic latitudes**
- **Additional data in database:**
  - **Polar CEPPAD/IPS proton flux database**
    - Includes 1996 through 1999 data (2000-2003 to be incorporated summer 2003)
    - Data values at higher magnetic latitudes than Geotail
  - **Extended Geotail EPIC/ICS proton flux database**
    - Include 1995-2001 data
    - Regime identifications at ~5 minute resolution of database
- **Code optimization**
  - **CRM Version 2 is faster than Version 1 even with additional computational complexity.**
    - Database generation is computationally intensive
    - Runtime model is efficient and fast

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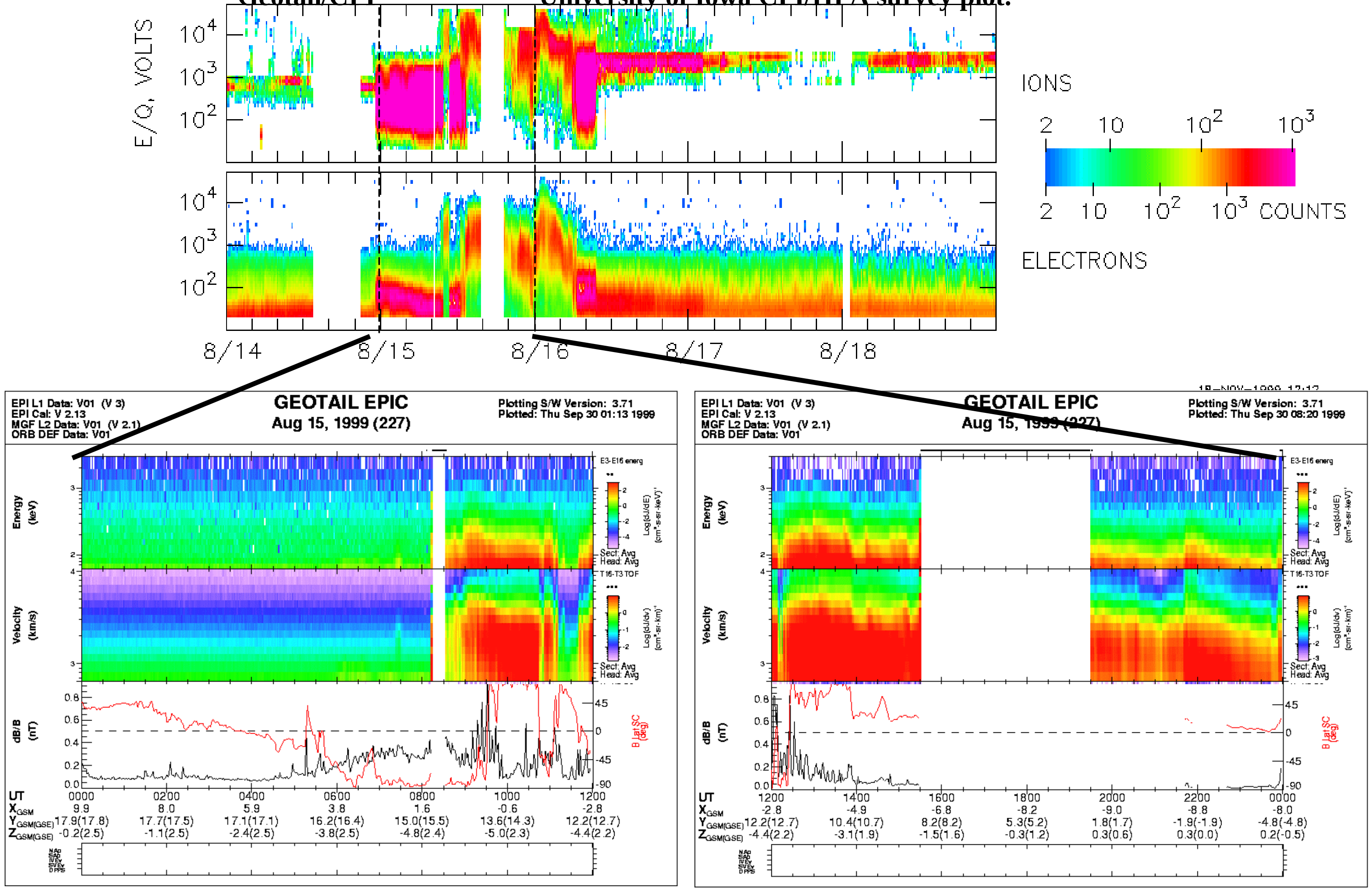
Geotail Plasma Regime ID

Geotail/CPI **University of Iowa CPI/HPA survey plot.**



JHU/APL EPIC/ICS survey plot.

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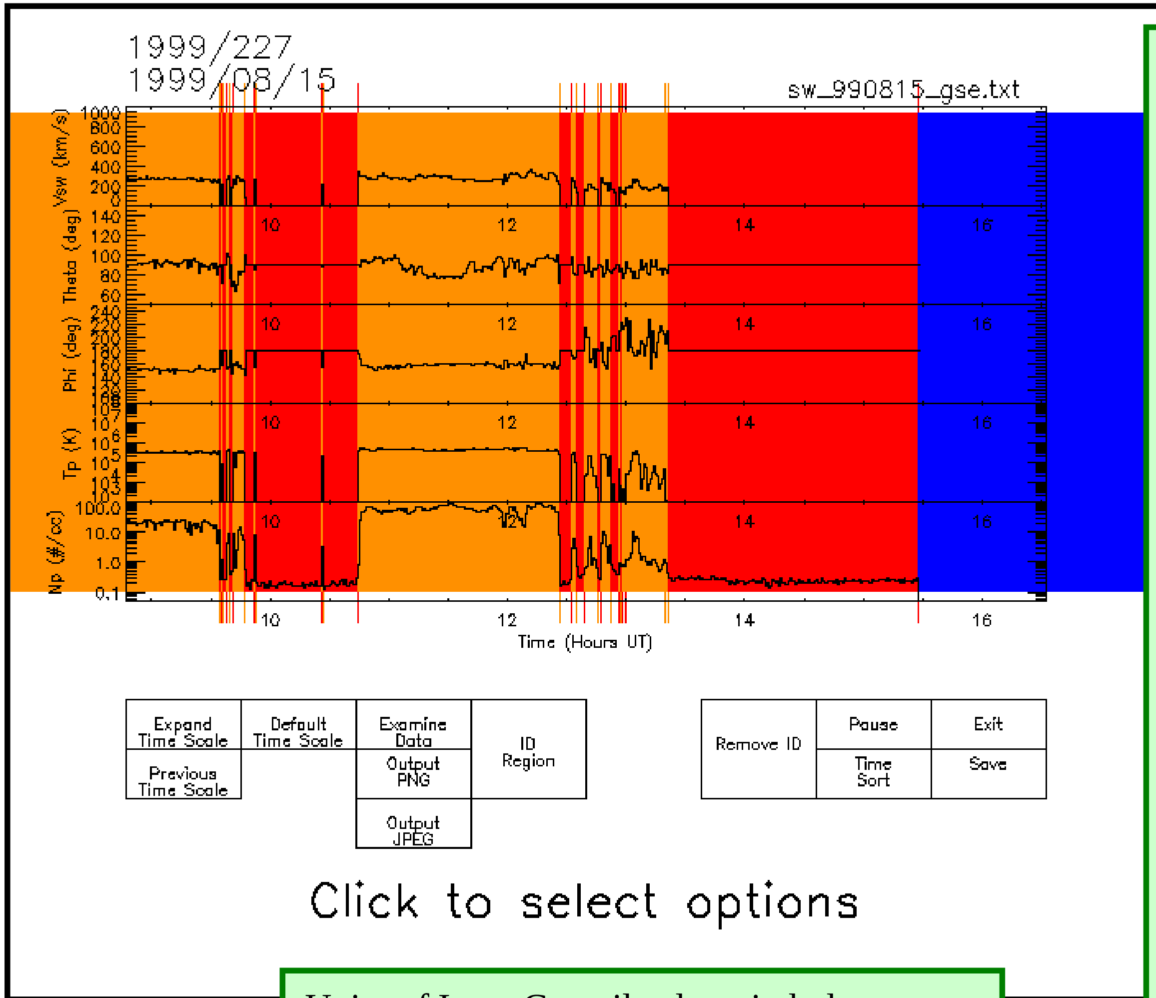
Plasma Regime Identification Tool



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Time (UT)	ID	Region
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9.57056	1	MS
9.58409	2	MP
9.59704	1	MS
9.62527	2	MP
9.66527	1	MS
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9.78646	1	MS
9.86823	2	MP
9.88186	1	MS
10.4373	2	MP
10.4506	1	MS
10.7353	2	MP
12.4470	1	MS
12.5427	2	MP
12.5821	1	MS
12.6496	2	MP
12.7589	1	MS
12.7859	2	MP
12.8681	1	MS
12.9345	2	MP
12.9616	1	MS

Univ. of Iowa Geotail solar wind plasma moments (CPI or SWA) used for regime identifications

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Streamline Flux Mapping

- **Step 1:** Create a database of "streamline" position points by computing ion test particle drift paths through the magnetosphere:

$$\vec{v}_D = \vec{v}_{\nabla B} + \vec{v}_{Curv} + \vec{v}_{ExB} = \frac{\vec{E}\times\vec{B}}{B^2} + \frac{m}{qB^4}\left(v_\parallel + \frac{v^2{}_\perp}{2}\right)\vec{B}\times\frac{\nabla B^2}{2}$$

  – conserving both the total energy and the first adiabatic invariant (the magnetic moment).

$$E_{tot} = \frac{1}{2}m\left(v_D{}^2 + v_\parallel{}^2\right) + \mu B + q\phi$$

- **Step 2:** Create a database of pointers that allow for the rapid mapping of a satellite particle flux measurement to a streamline.

- **Step 3:** Generate runtime database using spacecraft (Geotail, Polar) particle flux measurements
  – Map flux along field lines assuming isotropic flux distribution

$$J(B_p) = 4\pi\frac{B_p}{B_o}\int_{\sqrt{1-\frac{B_o}{B_p}}}^{\sqrt{1-\frac{B_o}{B_E}}}\frac{j_o(\cos\alpha_o)\cos\alpha_o\, d(\cos\alpha_o)}{[1 - \frac{B_o}{B_p}(1-\cos^2\alpha_o)]}$$

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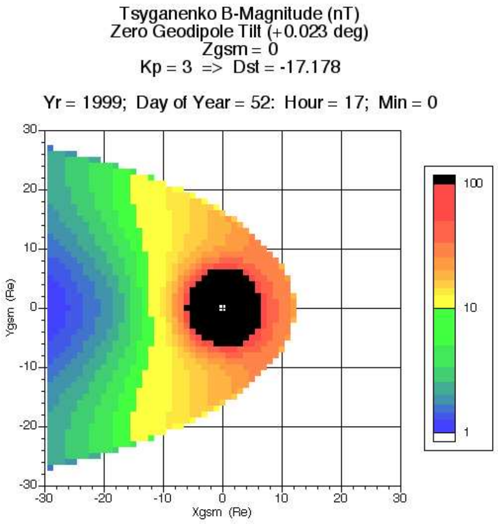
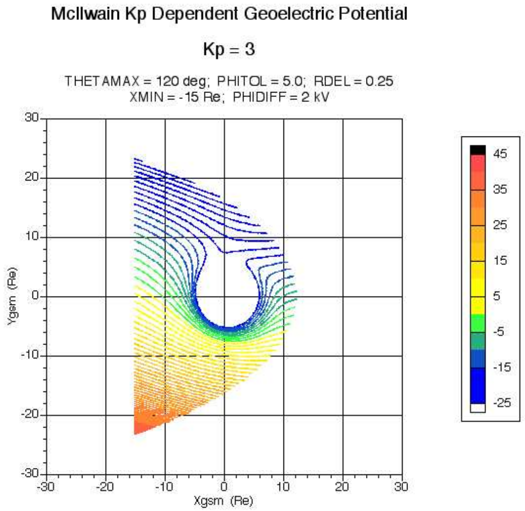
Streamline Generation

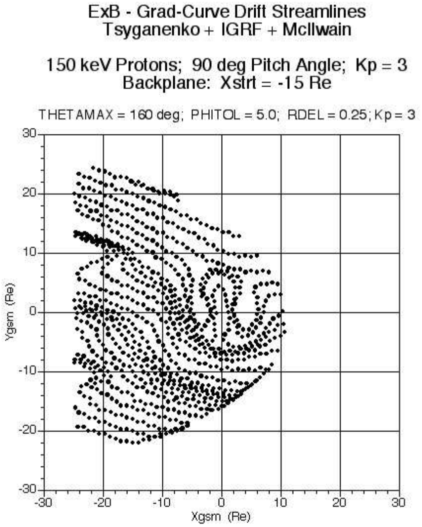
Magnetic Field Model
Tsyganenko

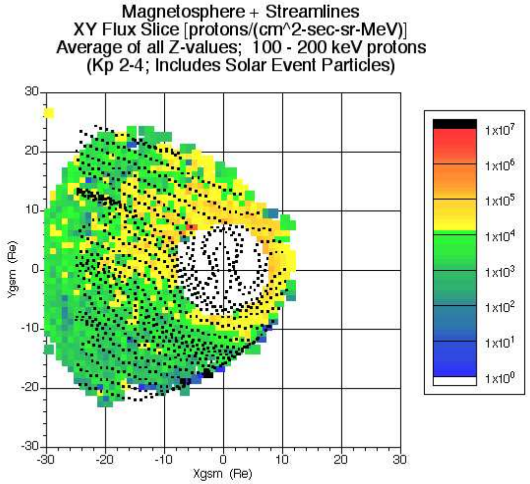




Electric Field Model
McIlwain Φ(Kp)

Streamlines





Streamlines overlayed
on Geotail flux

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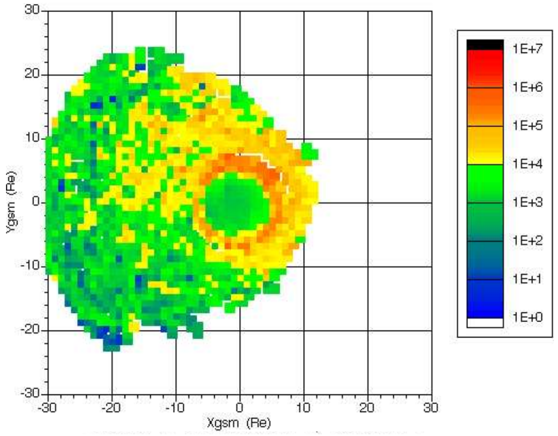
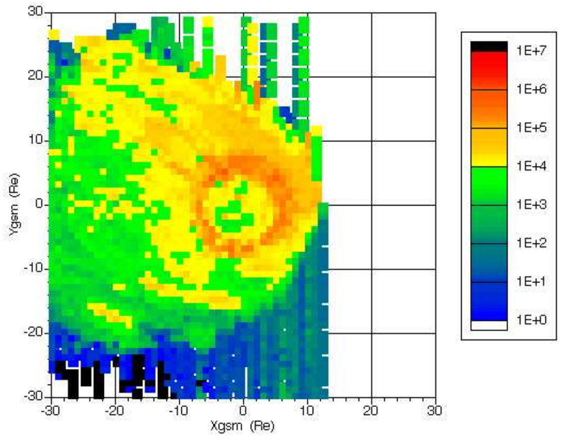
Streamline Flux Mapping

Individual Data
No mapping

Mapped Data

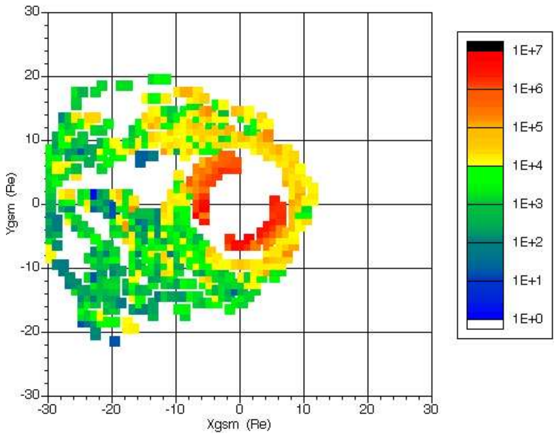
Kp 2-4
All data projected onto Z=0 plane

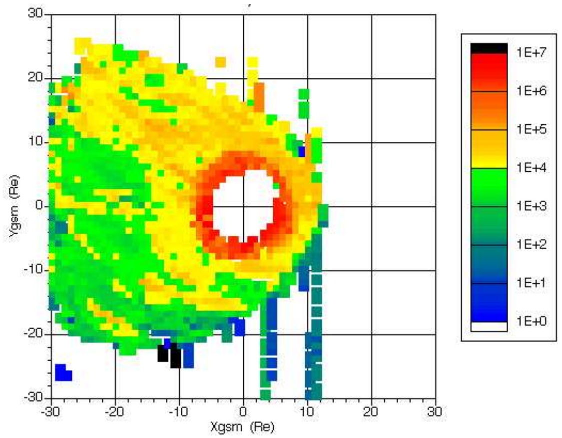




Kp 2-4
All data projected onto Z=0 plane

Kp 2-4
Data from -1<Z<1 projected onto Z=0 plane





Kp 2-4
Data from -1<Z<1 projected onto Z=0 plane

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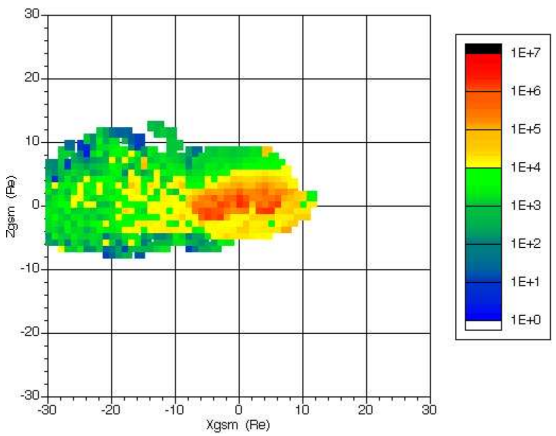
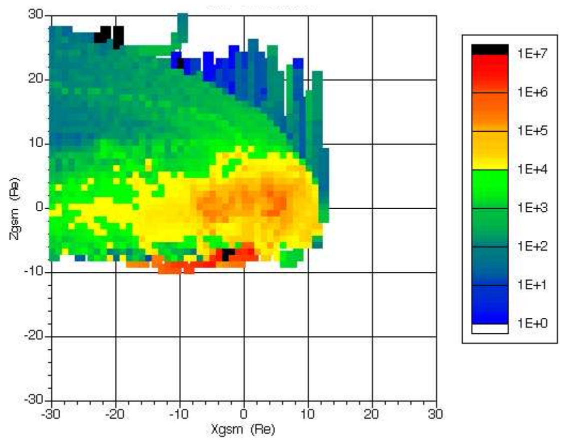
Streamline Flux Mapping

Individual Data
No mapping

Mapped Data

Kp 2-4
All data projected onto Y=0 plane





Kp 2-4
All data projected onto Y=0 plane

- Flux mapping yields a denser database
- Optimal use of available data (particularly at high Kp)

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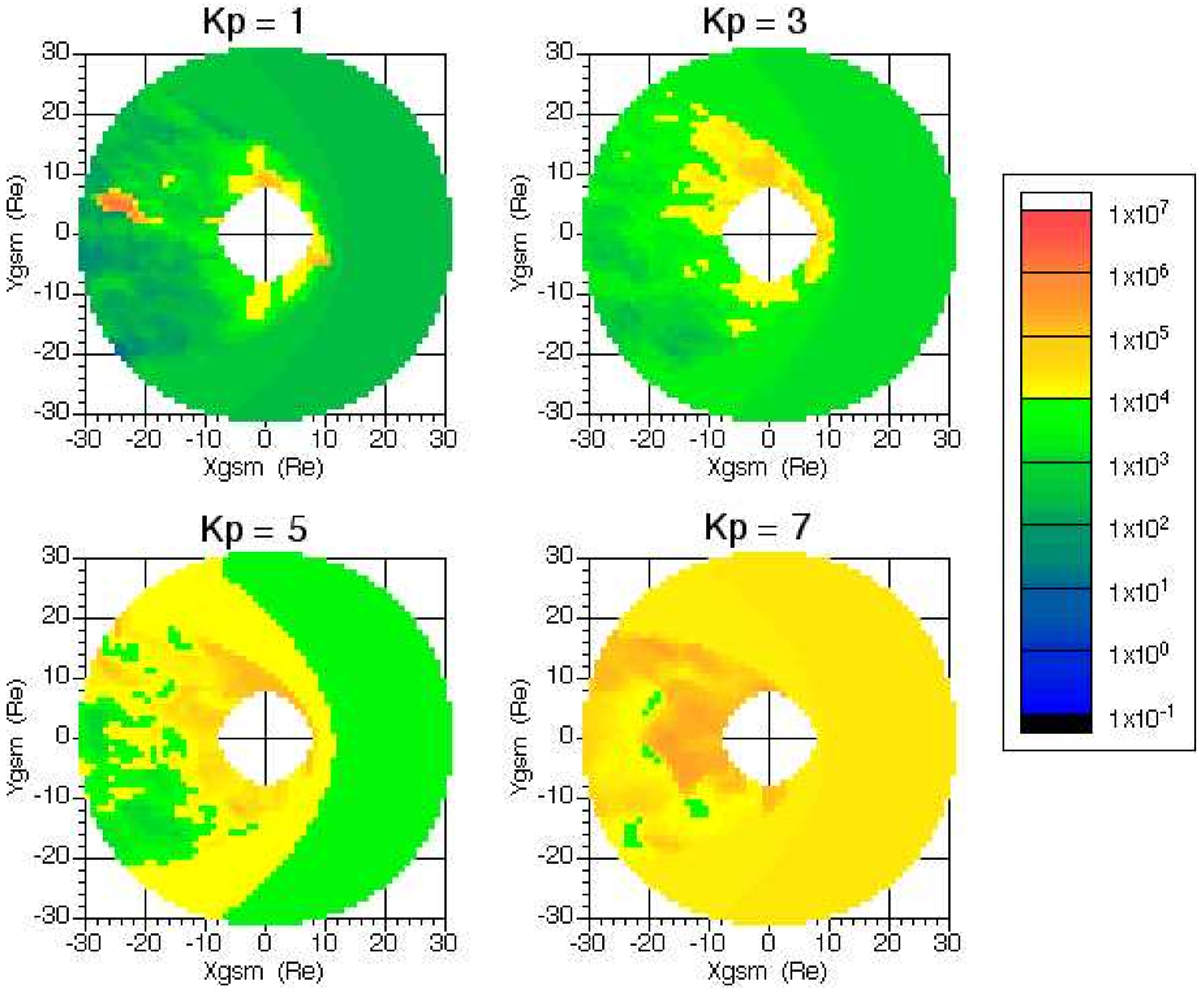
Proton Flux Output From CRMFLX V2



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Chandra Radiation Model Applications

- **Mission planning:**
  - CRMFLX incorporated into the CXO off-line system (OFLS) mission planning software to aid in determination of safe observation times for ACIS detector
    - CRMFLX with “mean” Kp input that yields acceptable flux, schedule events accordingly
  - AP-8/AE-8 in OFLS provides MeV proton, electron radiation belt boundaries
    - CRM provides additional low energy ion flux or fluence “events” to those determined for radiation belt passage using AP-8 model.
  - Tool for management of ACIS CTI degradation
    - Allows scheduling of science time that keeps CTI increase within allowed levels
- **Chandra Operations Center uses model as a near-real-time environment tool**
  - Assess the ion fluence for individual orbits
  - Situational awareness for spacecraft operations personnel
  - Implementation uses NOAA data for space weather input:
    - Real-time ACE/EPAM data for solar wind, magnetosheath
    - 3-hour K indices drive CRMFLX magnetosphere

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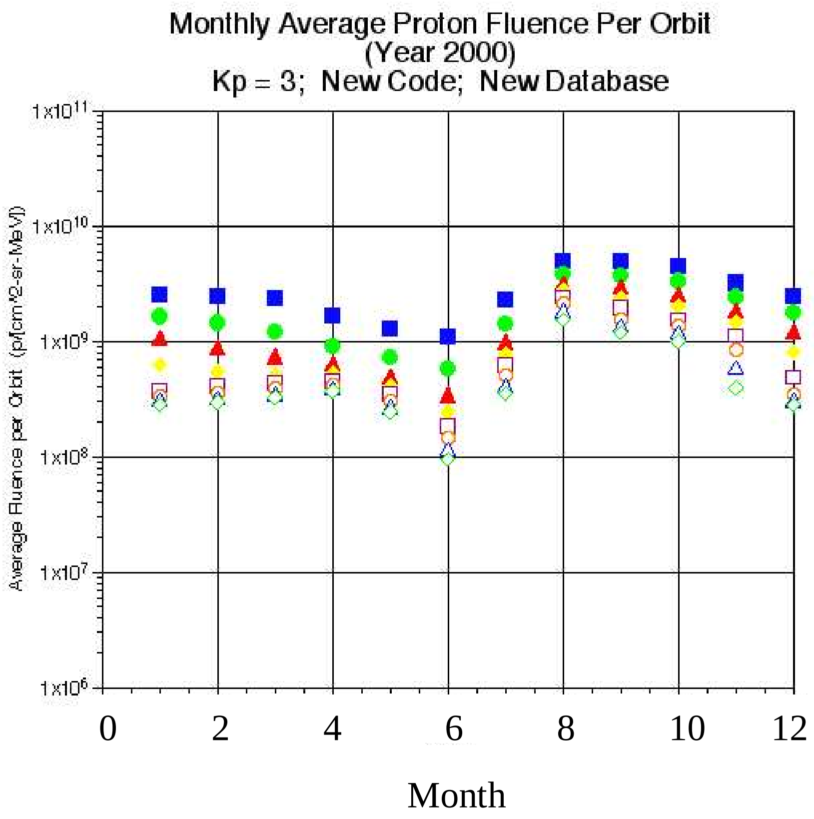
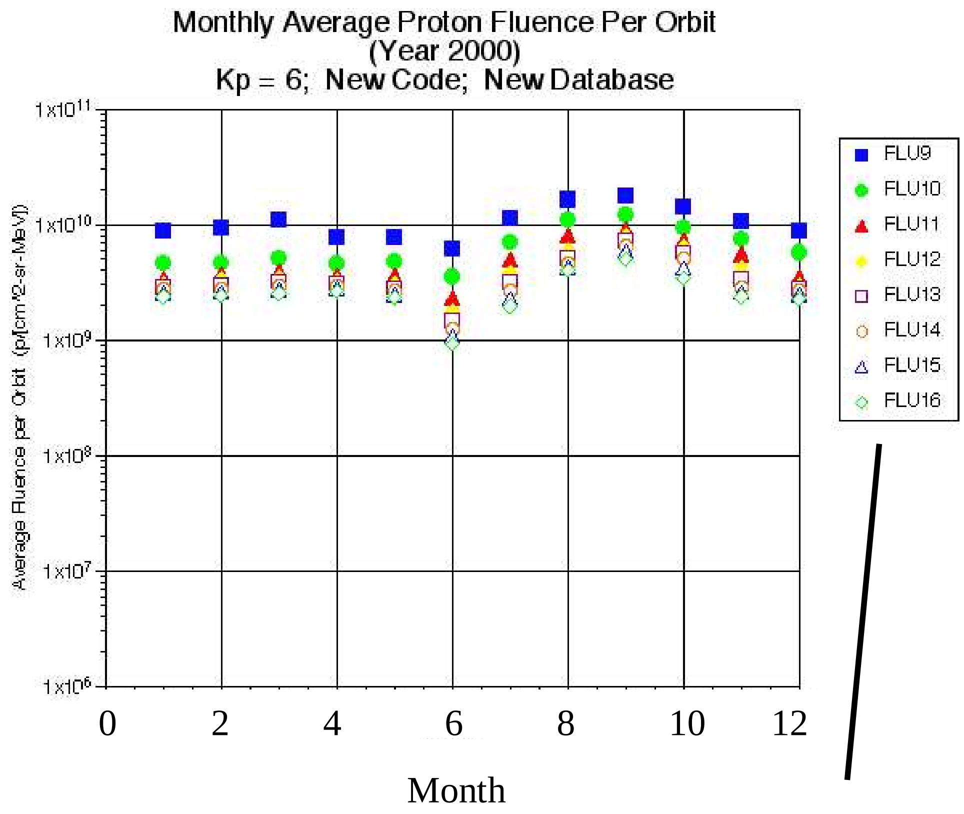
Monthly Average Fluence

CRMFLX V2.2 vs. CRMFLX V1





Kp = 3

Kp = 6

ACIS safing altitude (in Re)

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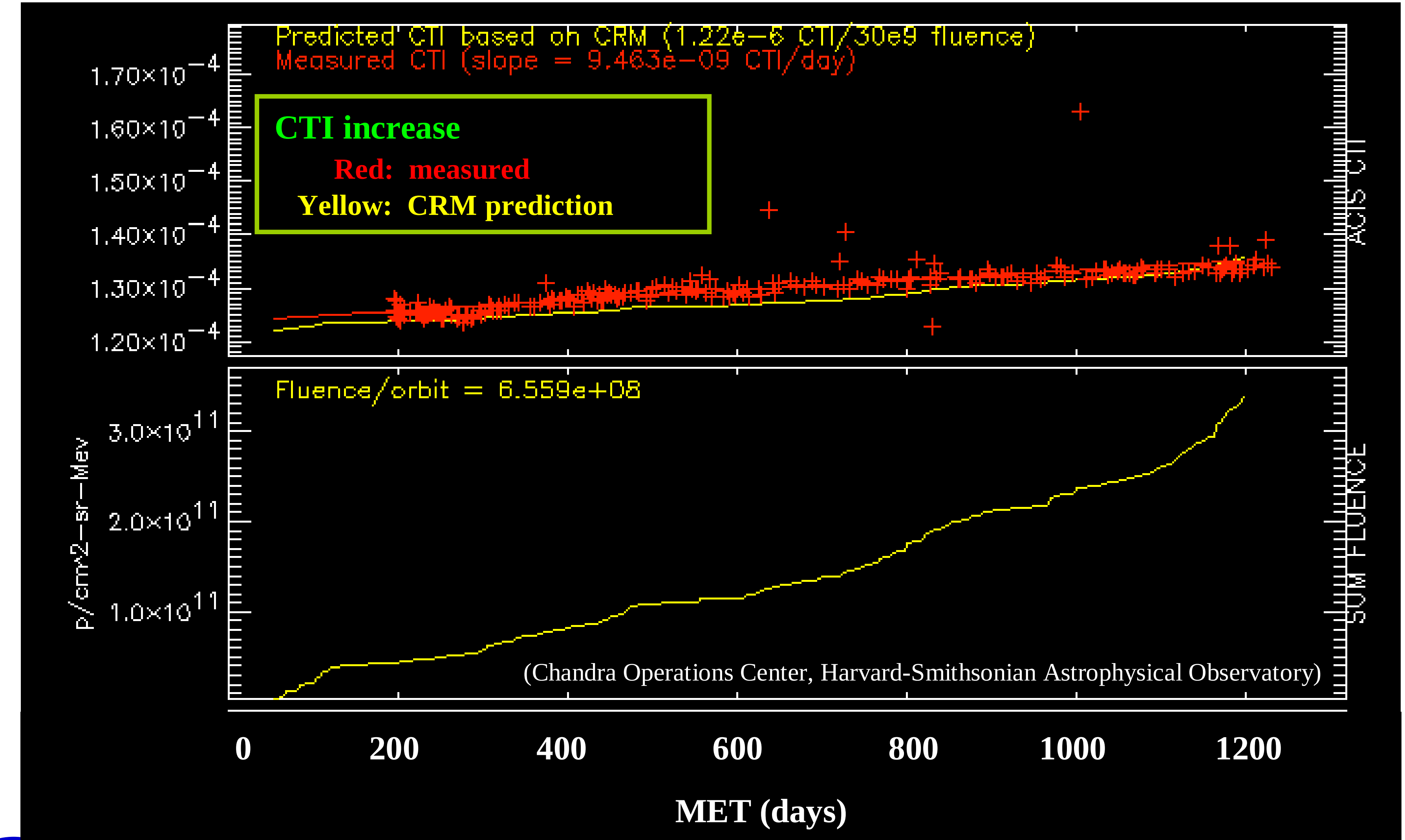
CTI Increase vs. CRM Proton Fluence



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Summary

- **CRMFLX is an empirical model of 100 –200 keV ion flux**
  - **Application tailored for addressing the Chandra ACIS radiation issue**
  - **Version 2 is a significant model upgrade over Version 1**
    - Streamline/fieldline mapping of data
    - Better representation of flux at high magnetic latitudes
    - Database more fully populated, better results at high Kp
- **Model status:**
  - **CRMFLX Version 2 released to Chandra Science Operations Center & Flight Operations Team for testing**
  - **CRMFLX Version 2 now incorporated into the Chandra Off-Line System (OFLS) scheduling software**
    - Analysis now being performed with CRMFLX to determine if science observation time can be increased while staying within budgeted CTI increase
  - **CRMFLX Version 2 in use at Chandra Operations Center as a near-real-time radiation environment monitoring tool**
    - Situational awareness for operators of 100-200 keV ion flux environment
    - Tests show that CRMFLX fluence predictions compare favorably with actual CTI degradation

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