25 Years of Radiation Protection of the Chandra X-ray Observatory.

Managing Unplanned Radiation Issues in Space

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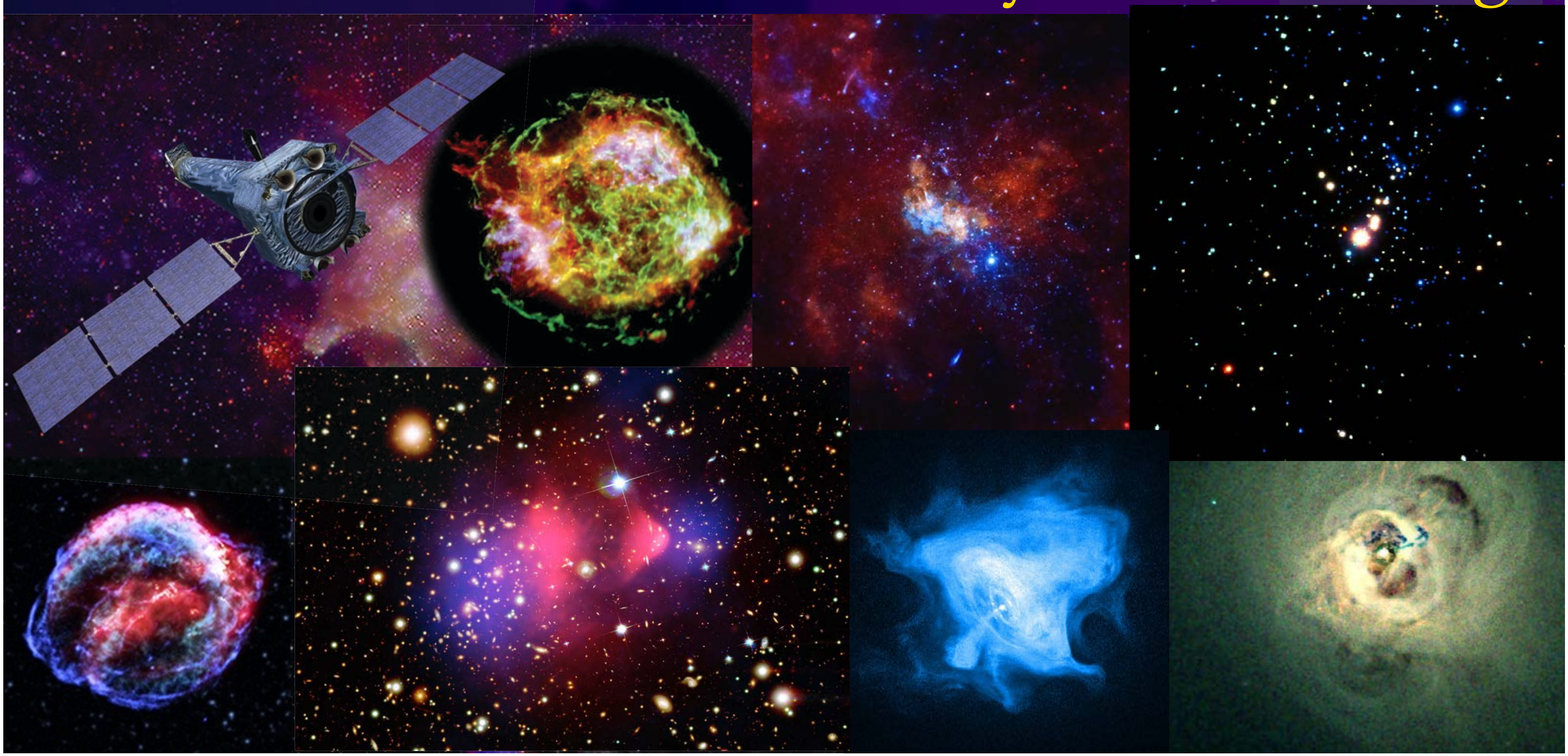
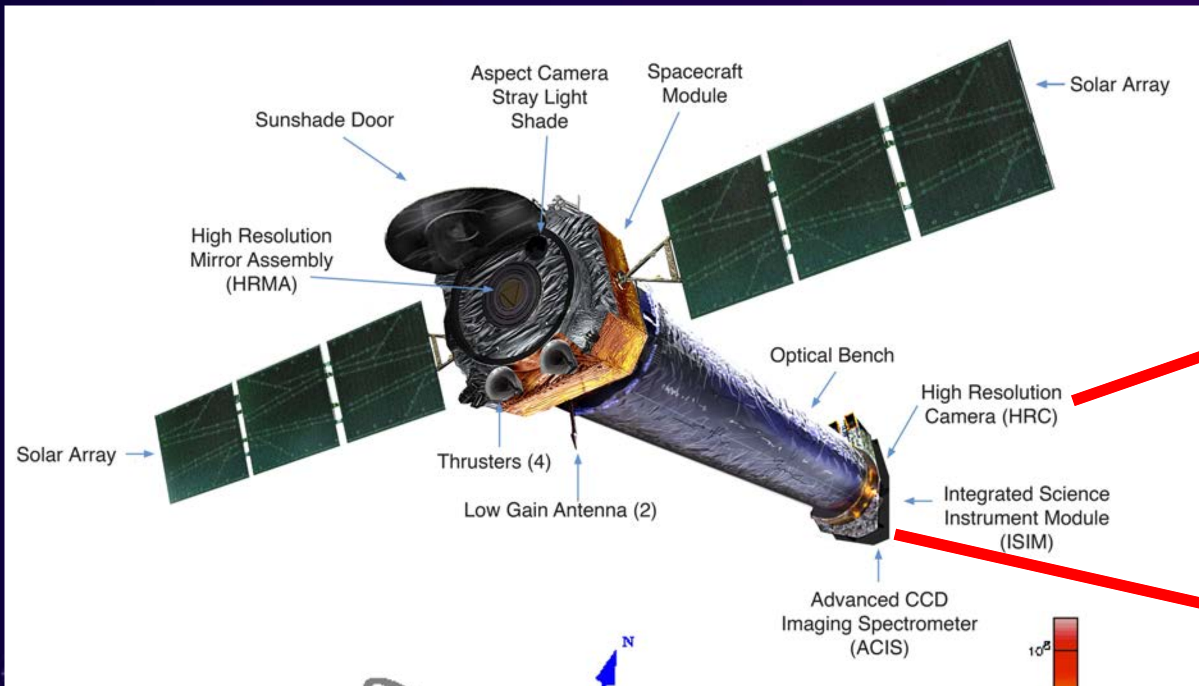
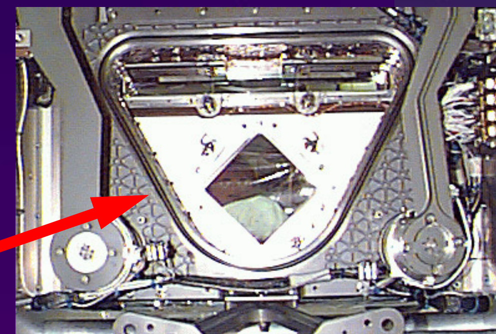
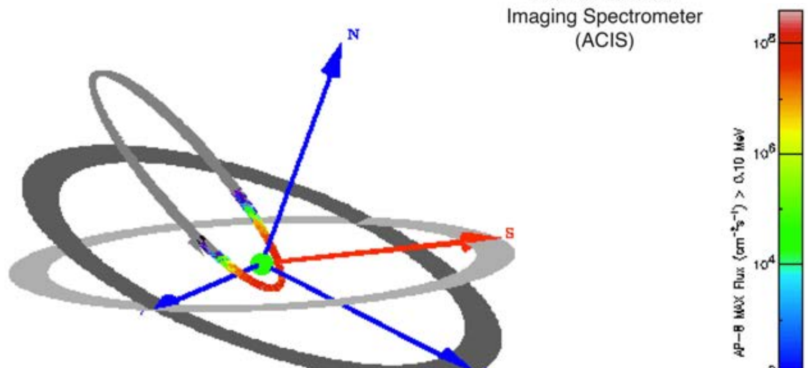
The Chandra Mission – MET 24 years & counting

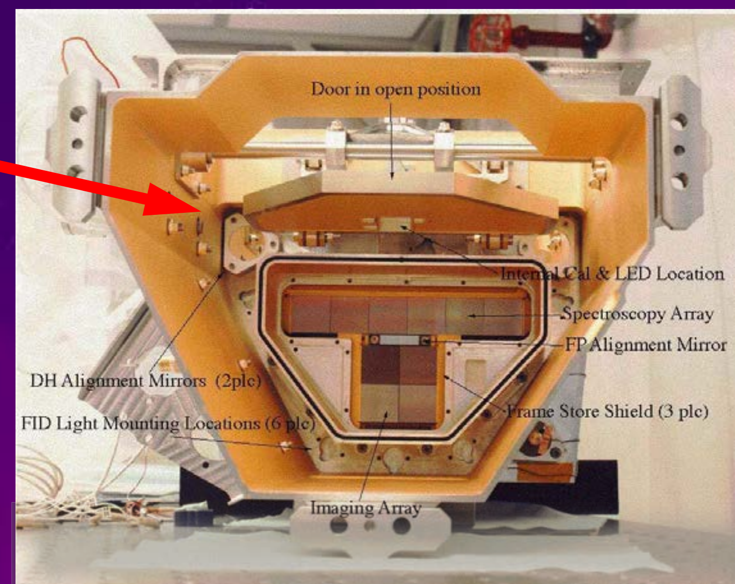








The starting orbit was highly elliptical and highly inclined, & intersected the VA Belts

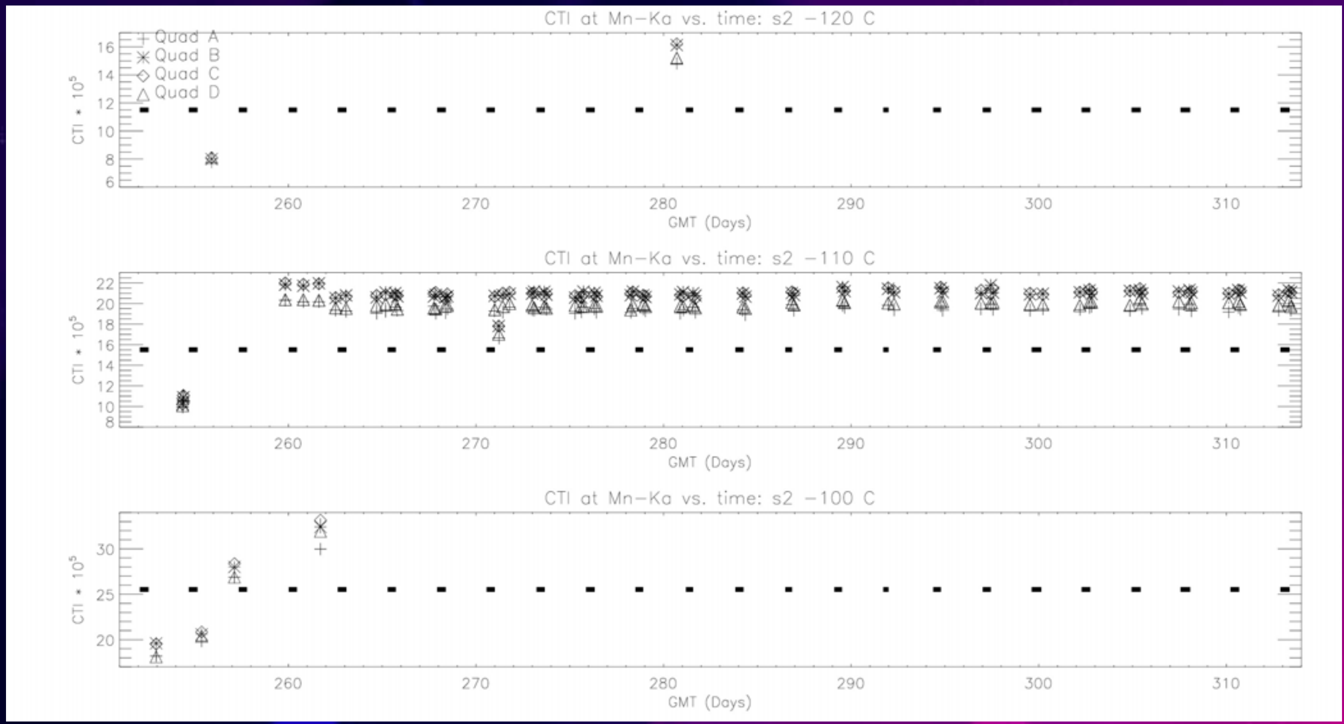


ACIS: A CCD-based imaging spectrometer

FI-CCD CTI degradation

Charge transfer inefficiency (CTI) of front-illuminated (FI) CCDs

- Original CTI was of order 10^{-6} i.e., 1 in 1,000,000 electrons were "lost in transit".
- Rapid increase in CTI (4×10^{-5}/orbit @ -100 °C) after first light



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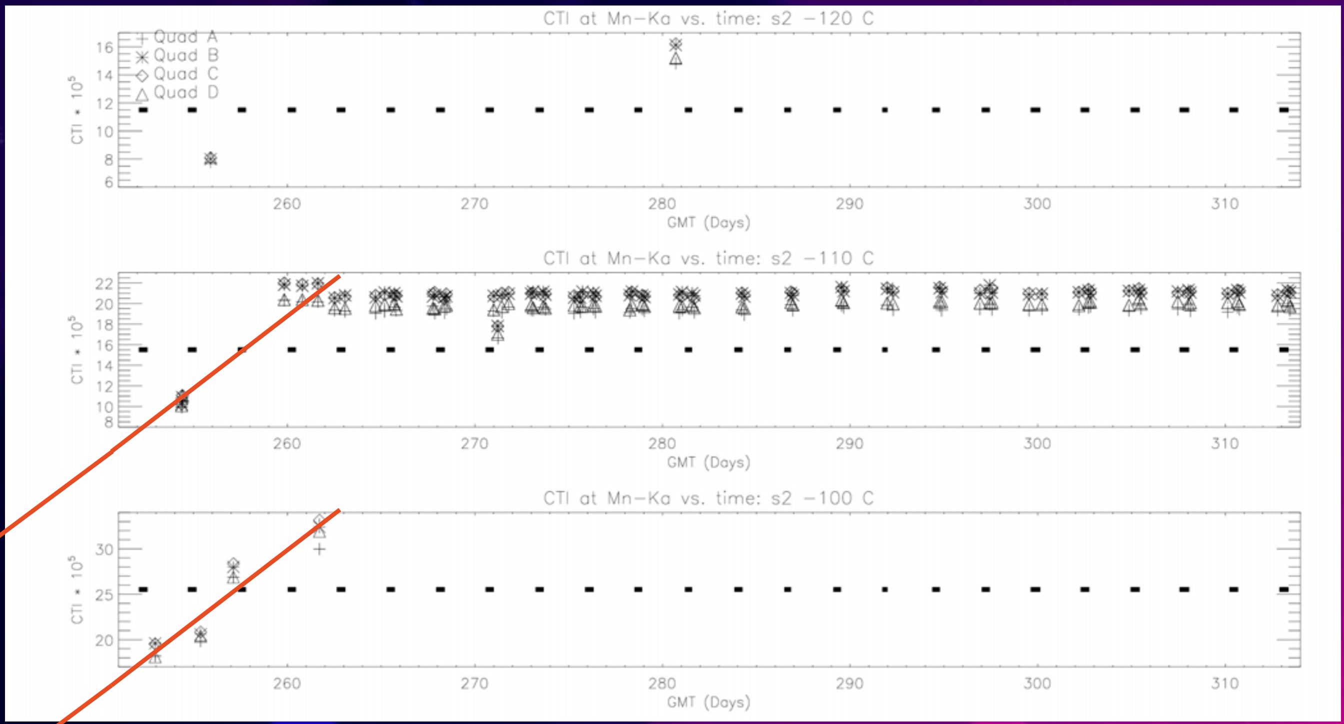

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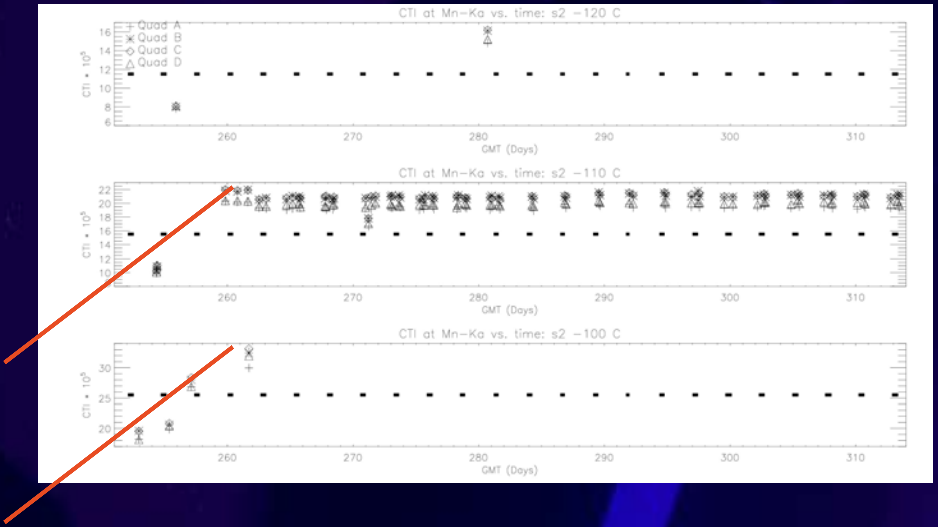
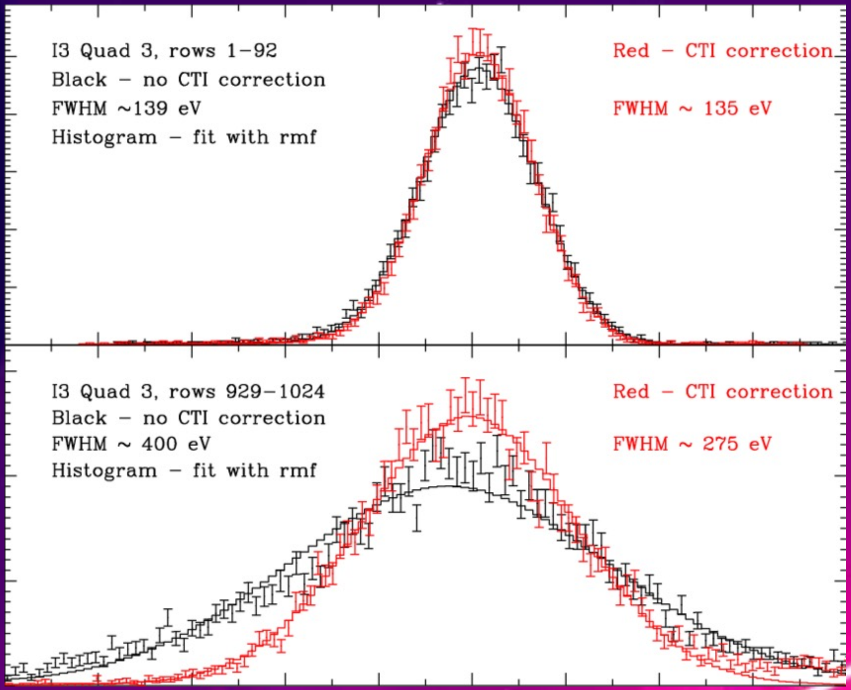
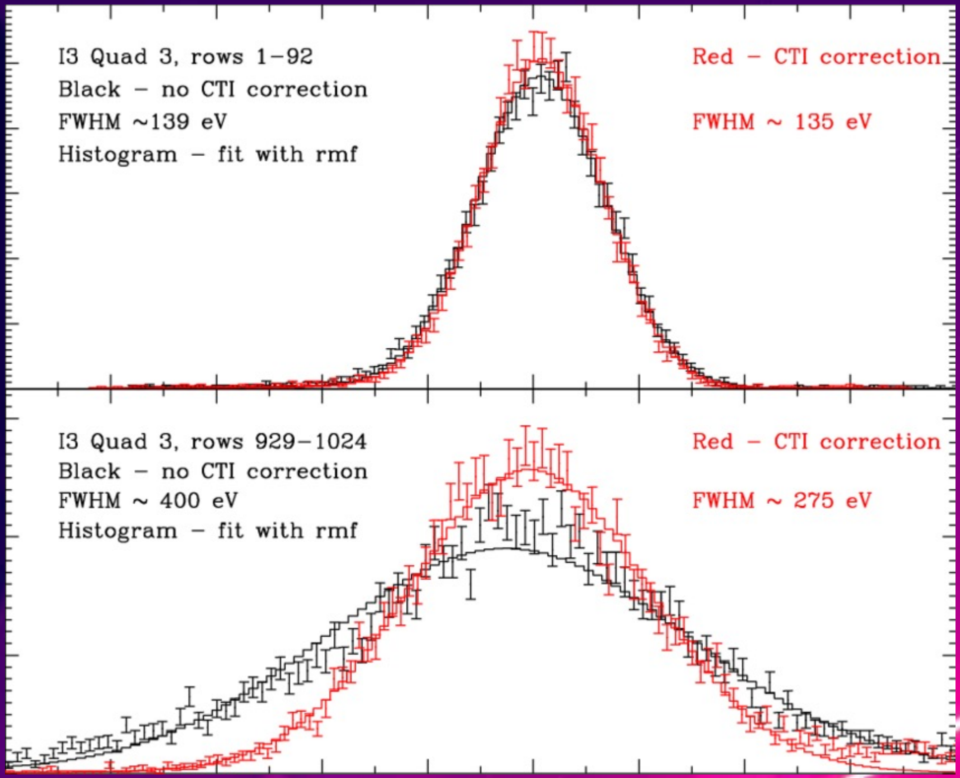




CTI Anomaly

- On-orbit evidence for damage by soft (0.1–0.5 MeV) protons
  - ACIS had been in the focal plane during 8 radiation-belt passages.
    - The focal plane is well shielded against penetrating radiation.
    - Line-of-sight shielding analysis missed scattering from mirrors.
  - No degradation occurred with ACIS in the next-in-line position during perigee.
  - Inserted gratings substantially reduced CTI degradation.
- CCD degradation mode suggested soft protons.
  - The increase in CTI of back-illuminated CCDs remained small.
    - BI CCDs have a 45-μm-thick Si shielding charge-transfer channel.
  - The dark current of all CCDs remained small.
  - Constant serial CTI showed that the frame-store area is shielded.
- Cal measurements before the light found no CTI degradation.
- SRIM transport to the focal plane is consistent with the AP-8 environment.
- On-ground proton irradiation of CCDs reproduced in-flight results.

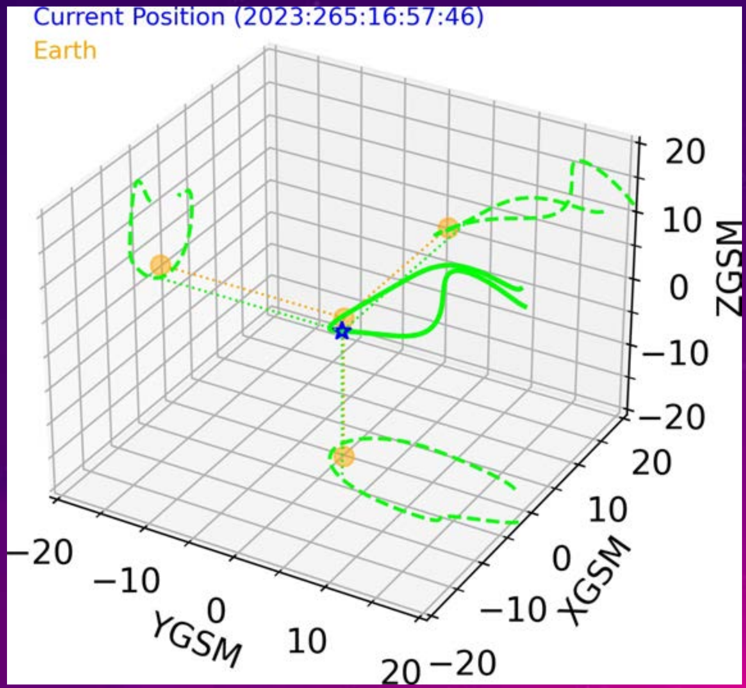


Mitigation Strategies

- Scheduled Protection
  - Move ACIS to NIL position for all radiation-belt passes.
    - Estimate inner-magnetosphere environment from AP-8.
      - Pad predicted boundary against inaccuracies and variations.
  - Lowered CCD temperature to –120 °C, reducing FI-CCD CTI.
- Autonomous Protection
  - Chandra radiation monitor (EPHIN) measures hard-proton flux.
  - Upon trigger, OBC halts loads and moves ACIS to a safe position.
    - Avoids rapid CTI degradation from rad-belt-config error or SEP.
- Commanded Intervention
  - Monitor the estimated soft-proton environment in Chandra's orbit.
    - Developed model for the entire Chandra soft-proton environment.
    - Use real-time space-environment data to drive the model.
  - When needed, halt load and command ACIS to NIL position
    - Typically wait for DSN contact, but can arrange special comm.

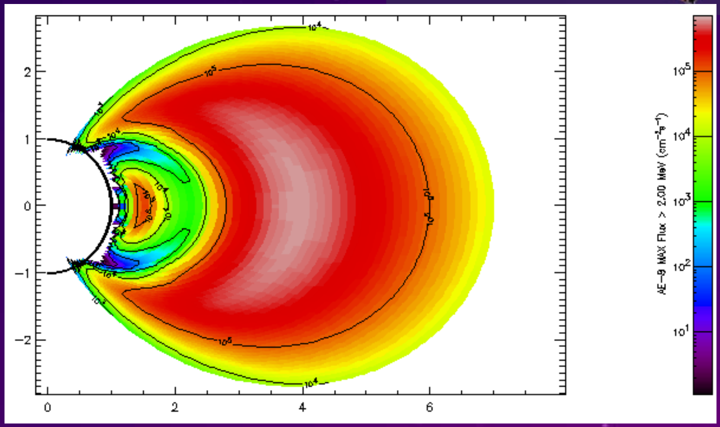
Mitigation Strategies: Scheduled protection

- The Chandra X-ray Observatory is in a highly elliptical orbit.
  - 140-Mm-altitude (23-$R_\oplus$ geocentric) apogee, 2.65-d period
  - 1-Mm-altitude (<1-$R_\oplus$ geocentric) perigee $\Rightarrow$ radiation belt
  - Real-time communication limited to DSN contacts
    - Nominally 3 DSN contacts/d for data dumps and commanding
    - Normally executes 1-week observing plan
- Revised operating procedures to protect ACIS against radiation.
  - Radiation-protection configuration
  - Translate ACIS into NIL position; power down video boards.
  - HRC in focal position; ramp down high voltage.
  - Retract LETG or HETG from the optical path, for most belt passages.
- Radiation protection during all belt passages



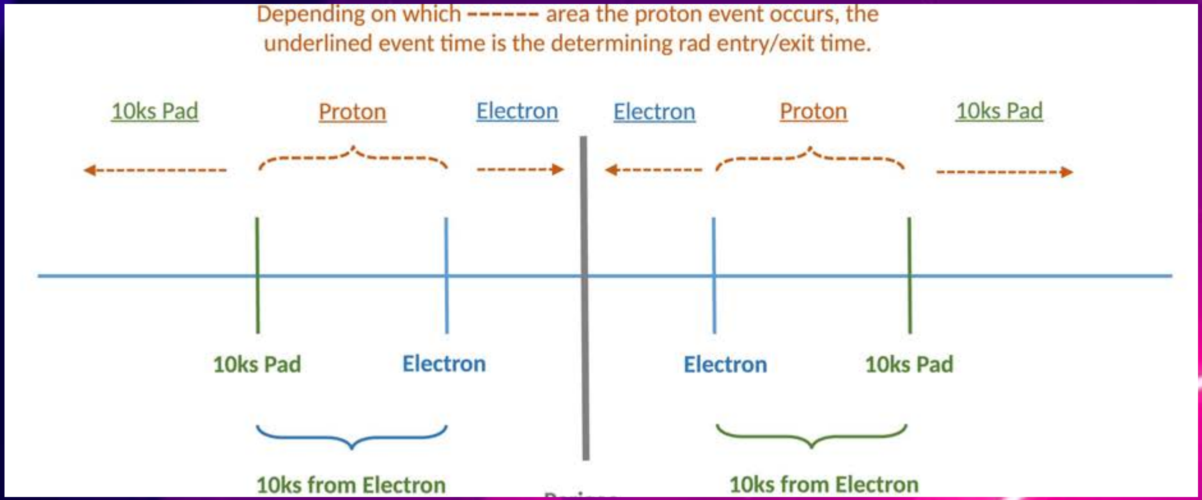
Mitigation Strategies: Scheduled protection

- Scheduled protection: 2000
  - Move ACIS to "Next in Line" position for all radiation-belt passes.
    - Estimate inner-magnetosphere environment from AP8.
      - Pad predicted boundary against inaccuracies and variations.



Since 2000

- Still use AE-8 / AP-8
- HRC limitations simplify Rad Zones
- High Energy Transmission Grating is now inserted as a failsafe.

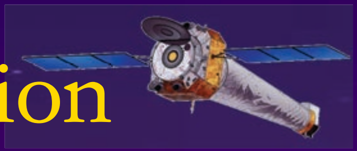


Ch-Ch-Ch Changes (Bowie 1972)

- October through December of 1999
  - Identification of SOFT protons as the hazard.
  - This corresponds to ACE P3 development of ground-based intervention based on ACE P3
  - Mapping ACE P3 to various EPHIN Channels for onboard safing.
- 2000: development of the Chandra Radiation Model
- 2001: EPHIN heating is apparent.
  - Start to plan to use HRC anti-co shields (map Ephin rates to Anti-co rates)
- 2007: EPHIN partially fails due to high noise in some channels
- 2011: ACIS software updated to be its own monitor
- 2014: EPHIN fully removed from service
- 2020: HRC-A side fails
  - ACIS monitors upgrade begins
- 2022: HRC-B side fails – no more HRC anti-co shields
  - ACIS monitors upgrade implemented

- Outside of the program:
- Several new iterations of GOES
- AP-9/AE-9 released
- SWPC comes online
- DSCOVR launched

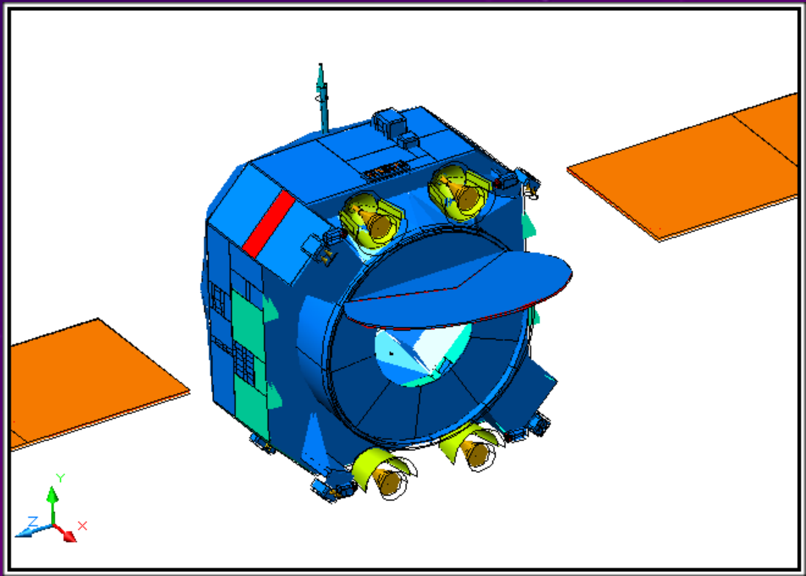
Mitigation Strategies: Autonomous Protection



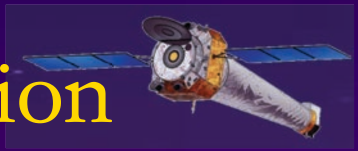
- Chandra radiation monitor (EPHIN) measures hard-proton flux.
- Upon trigger, OBC halts the mission loads and moves ACIS to a safe position.

The Electron Proton Helium INstrument (EPHIN) on Chandra is a SOHO flight spare sensitive to protons above 4 MeV.

- Various calibrations were made to map 100-200 keV protons (which cause the damage) to the available EPHIN Channels. These established on-board trigger levels.
- However, the EPHIN instrument is exposed on the Sun-facing side of the spacecraft.
- Certain channels failed from overheating by 2006

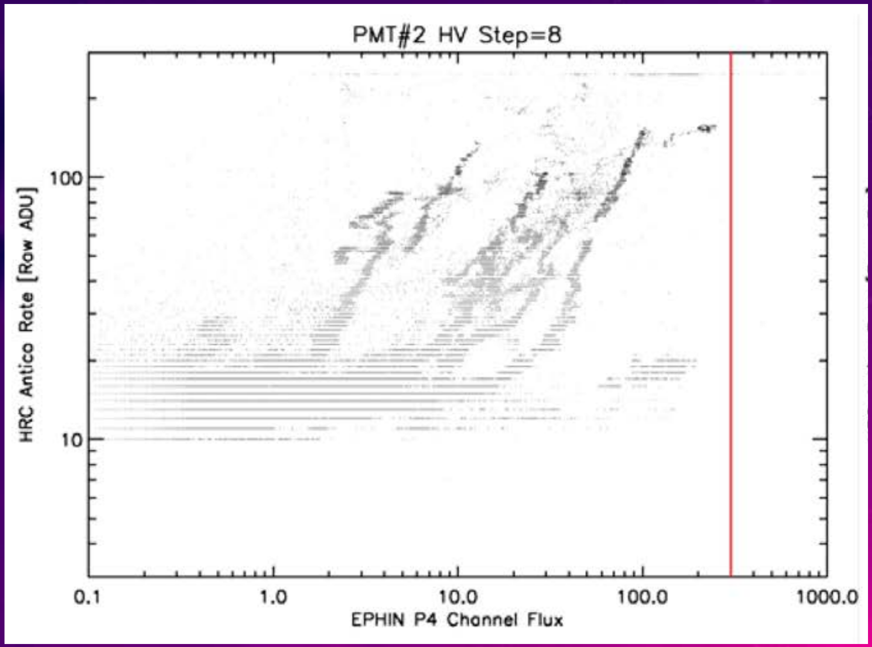


Mitigation Strategies: Autonomous Protection



- EPHIN
  - slowly failed
  - Certain channels failed from overheating by 2006
  - Became ineffectual by 2013
  - Hard failure 2017
- HRC anti-coincidence shields (added ~2005)
  - The anti-co shield rate could be used a proxy for the EPHIN rates (which were a proxy for the real rates as determined by ACE)
  - "HRC anti-co data are a poor substitute for EPHIN data" (O'Dell 2005).
- ACIS rejected events rate
  - Added in 2011
  - Set to trigger at a threshold to not cause false trips.

HRC Anti coincidence shield rates vs. EPHIN rates



Mitigation Strategies: Autonomous Protection

- ~~EPHIN slowly failed~~
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  - ~~Became ineffectual by 2013~~
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- ACIS rejected events rate
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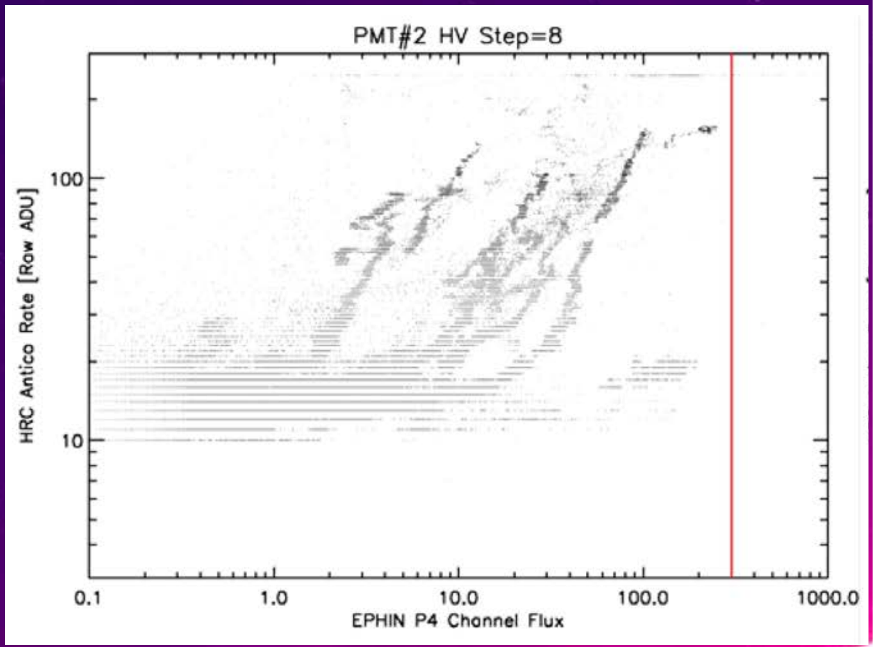
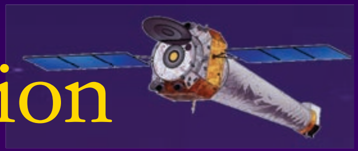
  - Set to trigger at a threshold below EPHIN

HRC Anti coincidence shield rates vs. EPHIN rates



Mitigation Strategies: Autonomous Protection



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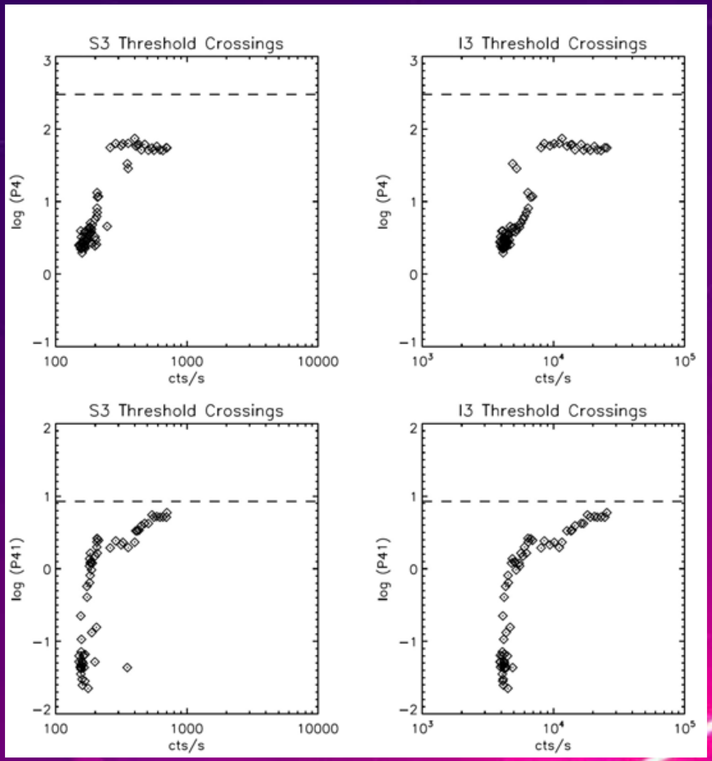
  - HRC Side A failed in 2020
  - HRC Side B failed in 2022
  - HRC Side A now runs in a mode that limits shield use.
- ACIS rejected events rate
  - Added in 2011
  - Set to trigger at a threshold closer to EPHIN in 2022

ACIS Threshold crossings as a function of EPHIN rates



Mitigation Strategies: Autonomous Protection

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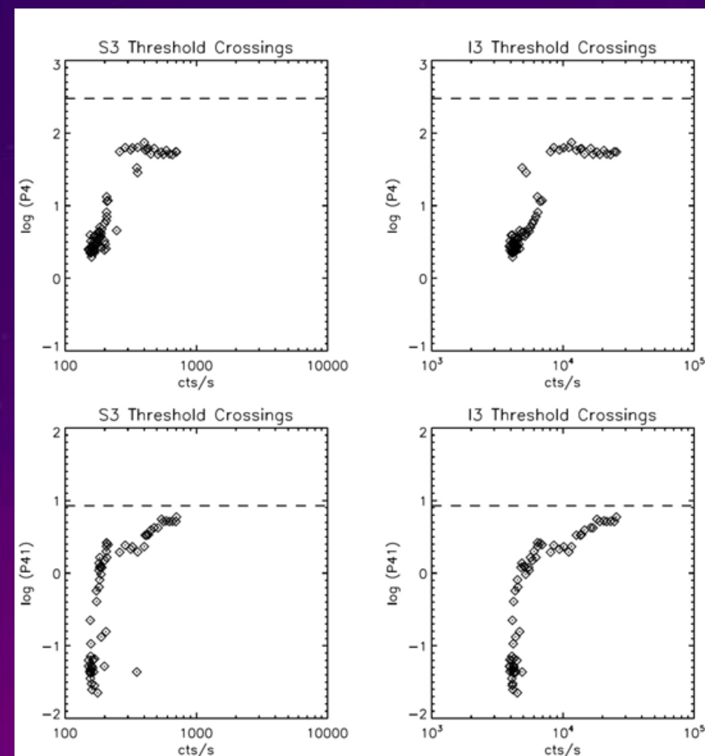

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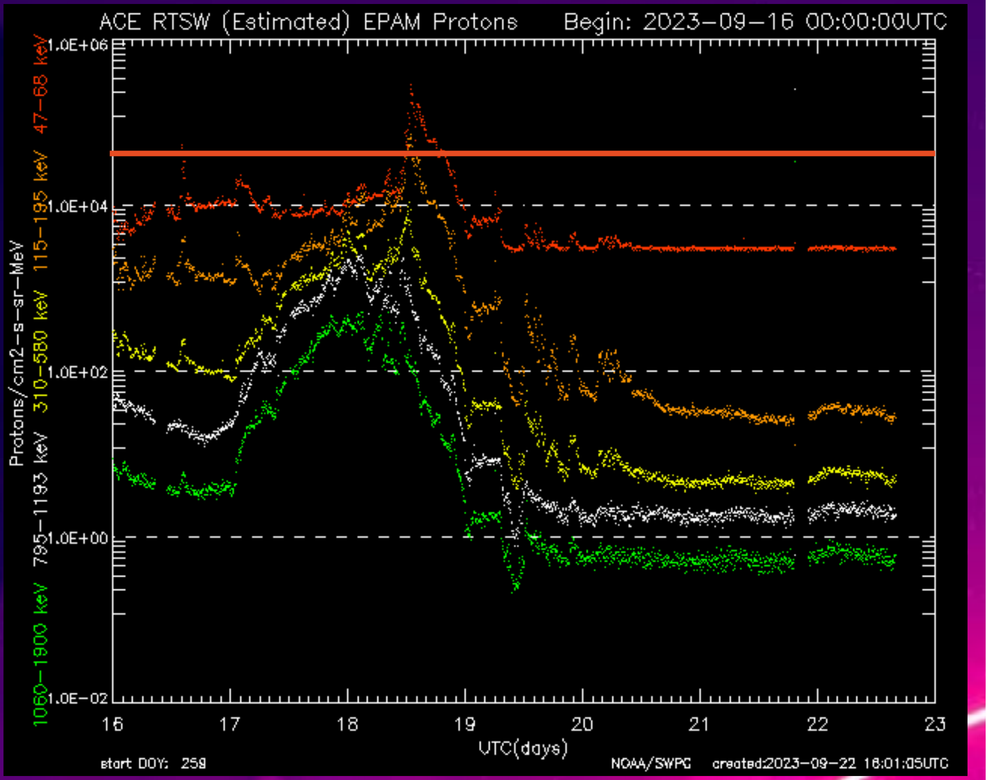
Mitigation Strategies: Commanded Intervention

- Monitor the estimated soft-proton environment in Chandra's orbit.
  - ACE (NOAA; launched in 1999) is the only spacecraft (we are aware of) that directly monitors the relevant protons.
  - Real-time proton environment
  - Damaging protons
    - EPAM-P3 channel ~140-keV protons
    - CXC alert if fluence high (> 50,000)
    - We also adopted an orbital fluence limit of $2x10^9$
  - When needed, halt load and command ACIS to a safe position.
    - Since 2011 science loads are halted but spacecraft maneuvers continue.
    - Typically wait for DSN contact.



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  - Real-time proton environment
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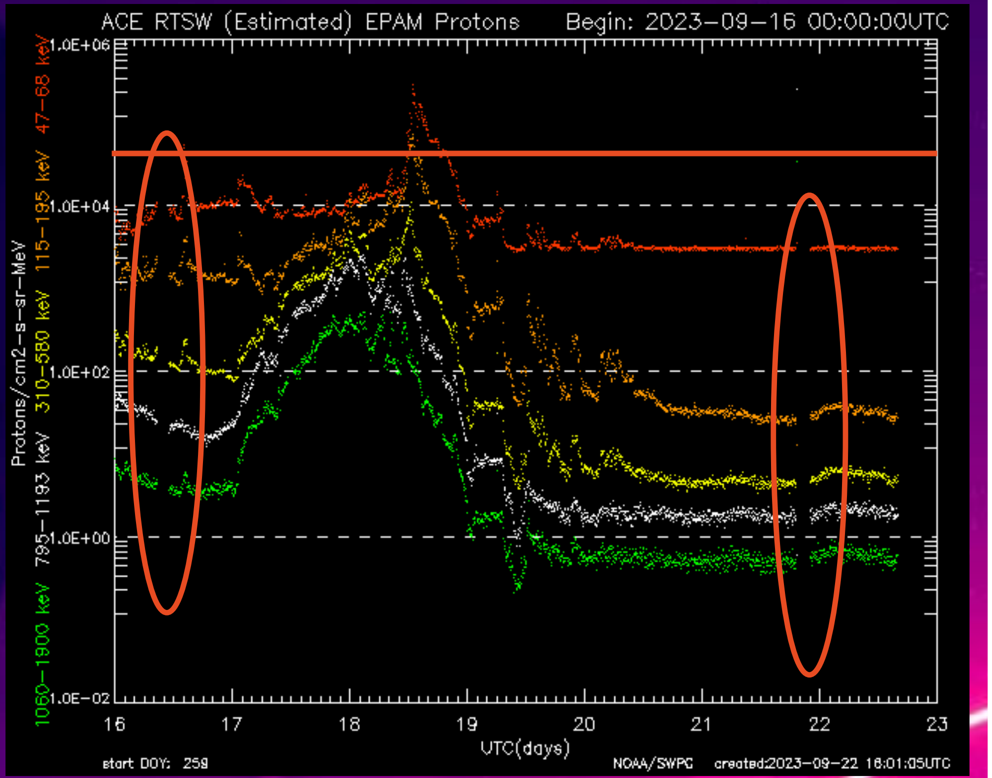
    - EPAM-P3 channel ~140-keV protons
    - CXC alert if fluence high
  - ACE is no longer officially supported. We thank the team for a huge effort on our behalf.



Mitigation Strategies: Commanded Intervention

- Monitor the estimated soft-proton environment in Chandra's orbit.
  - ACE (NOAA; launched in 1999) is the only spacecraft (we are aware of) that directly monitors the relevant protons.
  - Real-time proton environment
  - Monitor for shock passage
  - When needed, halt load and command ACIS to a safe position.
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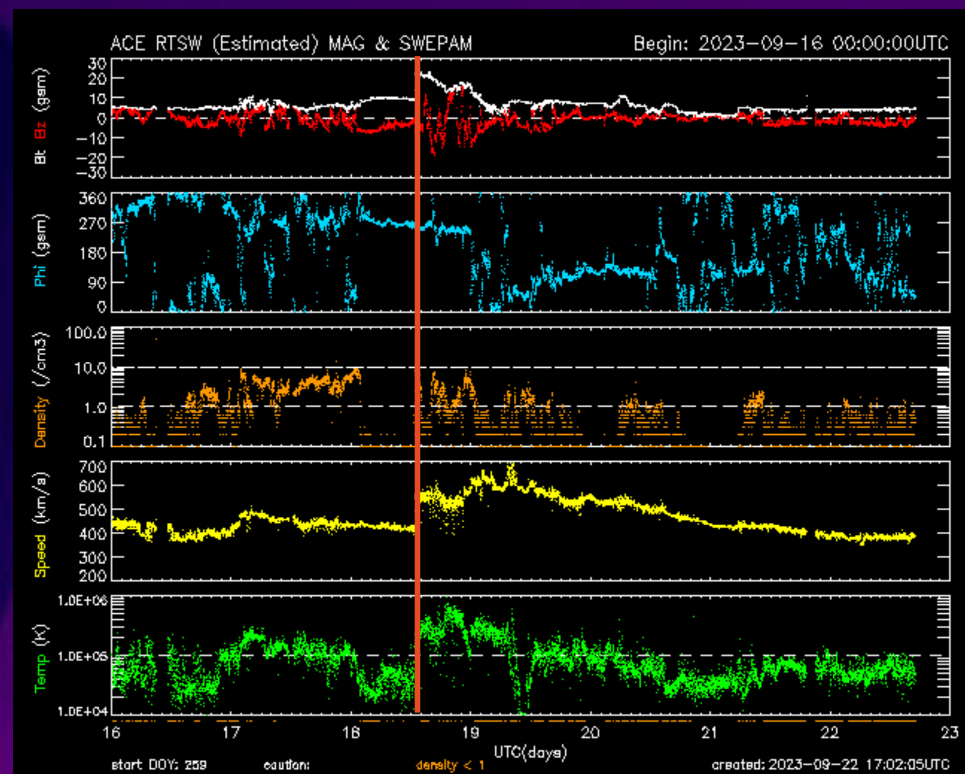
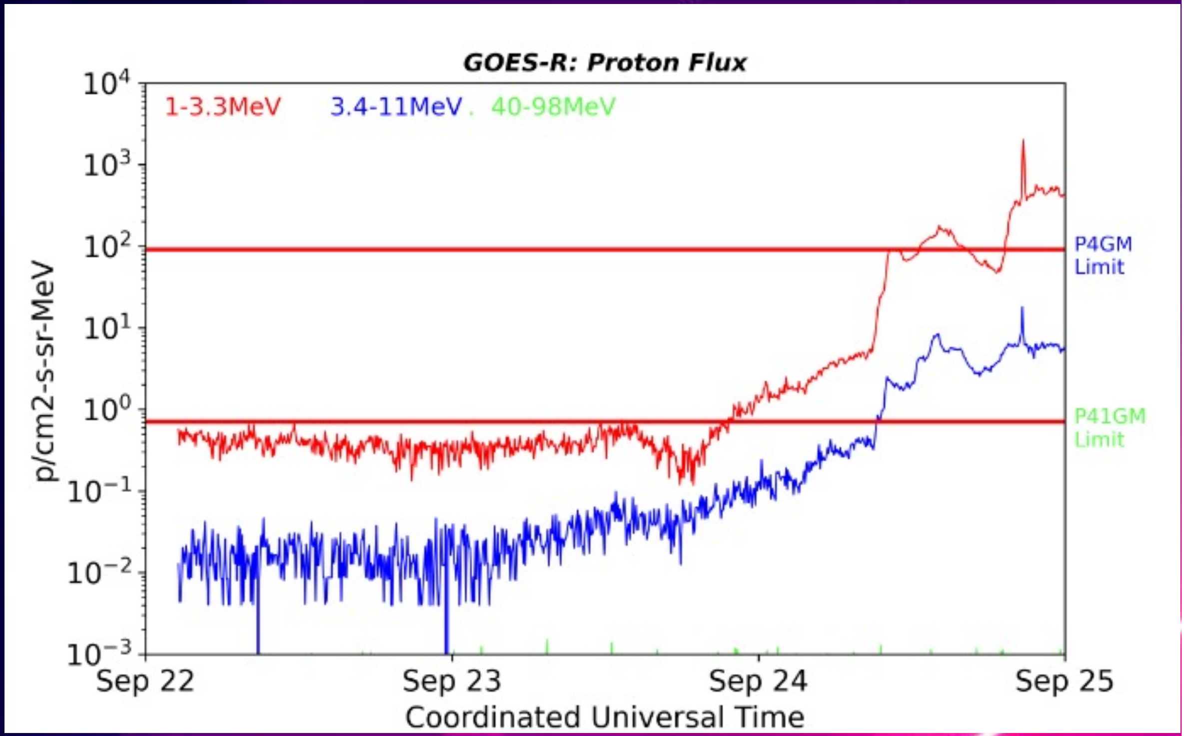


Mitigation Strategies: Commanded Intervention

Other External Data Sources:

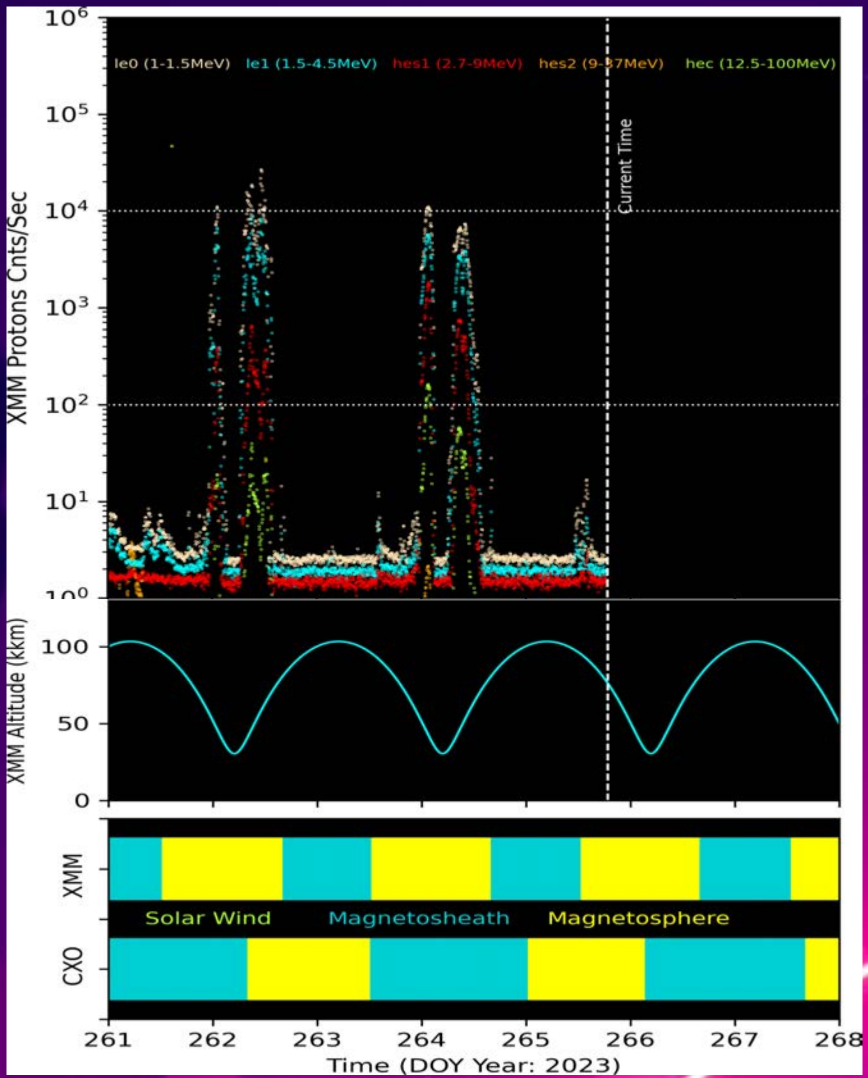
- GOES-EPHIN Estimator
- NOAA SEC data
  - We started with GOES-8
  - Now using GOES-R
- RT hard protons
  - Use for Chandra
  - Indicator of autonomous safing
  - GOES-8:P2 ➔EPHIN-P4
  - GOES-8:P5 ➔EPHIN-P41

Solar protons > 5 MeV typically penetrate to geosynchronous orbit (6.6 $R_{\oplus}$).



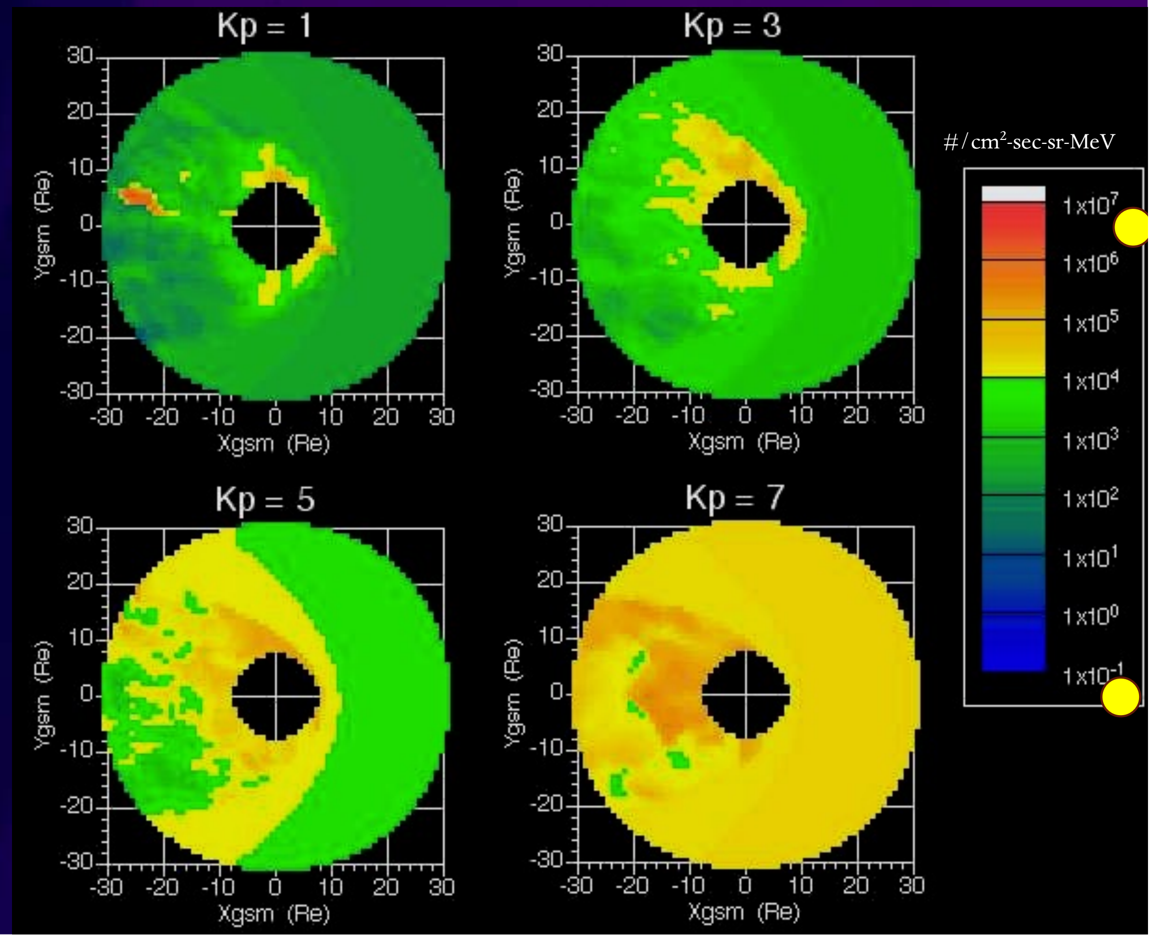
Other data in use:

- GOES Solar X-ray Monitor:
  - M5 flares and above give us pause, especially if in neutral or western longitudes
  - LASCO to confirm any related CME
- WSA-ENLIL solar wind prediction
  - Timing the arrival of the shock is critical to replaning and intercept timing.
- Coordinated Community Modeling Center CME Scoreboard
  - Head start on re-planning
- DSCOVR: For shock passage
- SOHO: For shock passage
- XMM data: at similar altitude



Chandra Radiation Model

- The Chandra Radiation
  - Archival-data-based CRM
  - 0.14-MeV protons
    - Geotail EPIC
    - Polar CEPPAD
  - Streamline mapping
    - GSM coordinates
  - Correlated to Kp
    - Magnetosphere
    - Magnetosheath
    - Solar wind
- CRM flux
  - Calculate flux in orbit
  - Integrate to fluence
  - Project future fluence



Chandra Radiation Model

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  - Calculate flux in orbit
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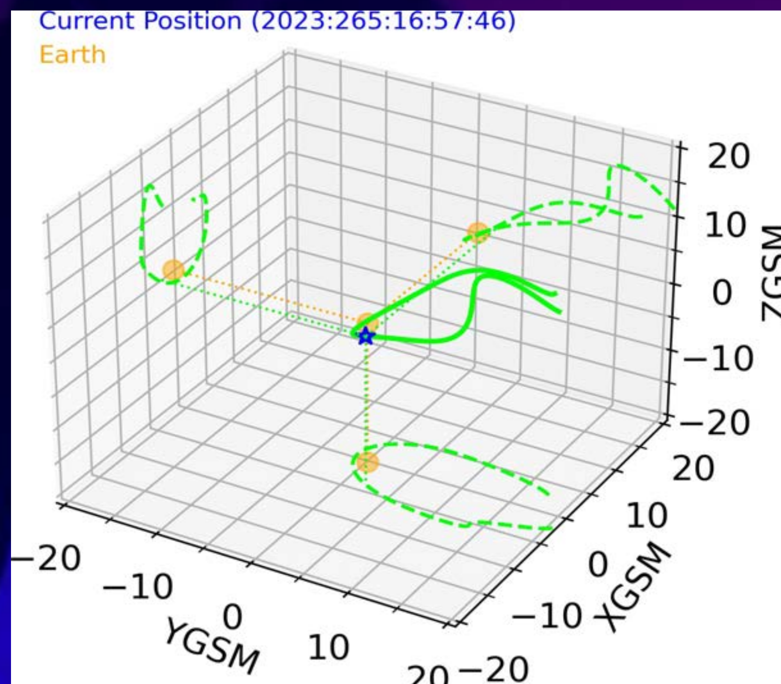
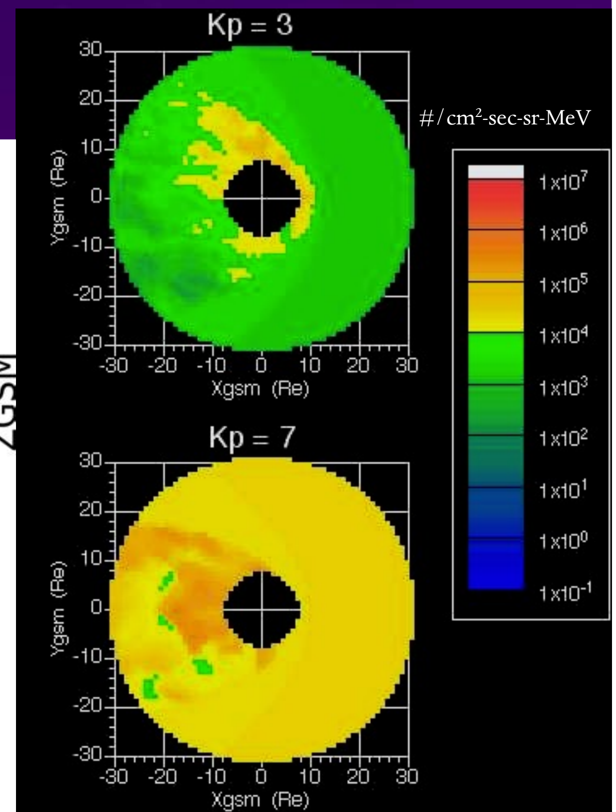
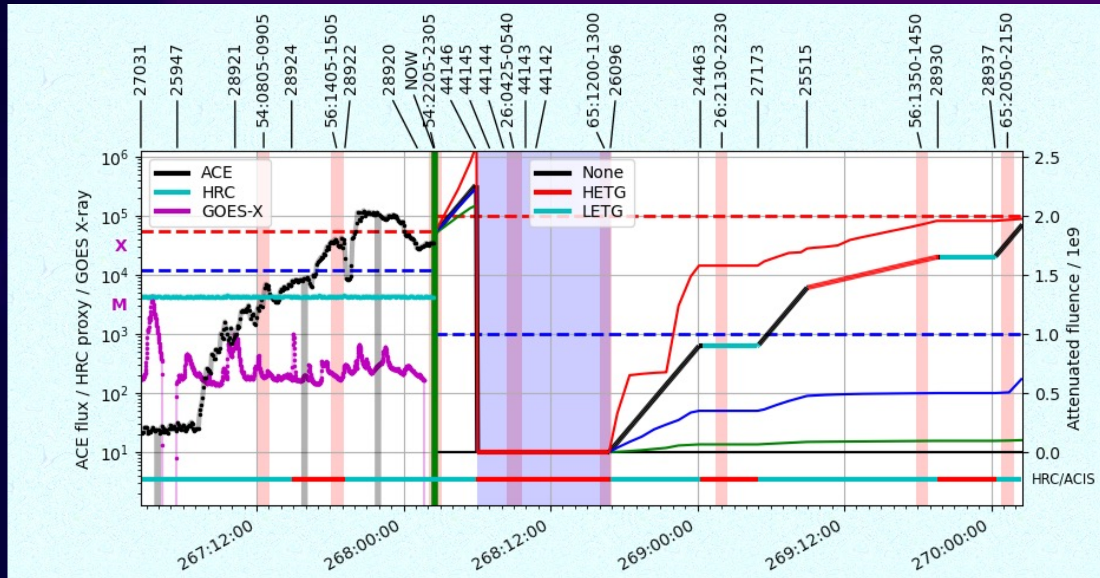
- 1. Solar wind $F_1(t) = F_{EPAM}(t)$
- 2. Magnetosheath $F_2(t) = 2 \times F_{EPAM}(t) + F_{CRM}(Kp(t))$
- 3. Magnetosphere $F_3(t) = F_{CRM}(Kp(t)) + ½ \times F_{EPAM}(t)$





Commanded Intervention: Case Study

- *ACIS Orbital Dose* limit was designed as a budgeting device.
  - We allowed 10 events per year exceeding 2x10^9 in fluence.
  - Over a 10-year mission, this would limit the Delta in CTI to < a factor of 2.
    - We have done much better than this!
  - This helps drive decision-making in "mild storm" conditions.

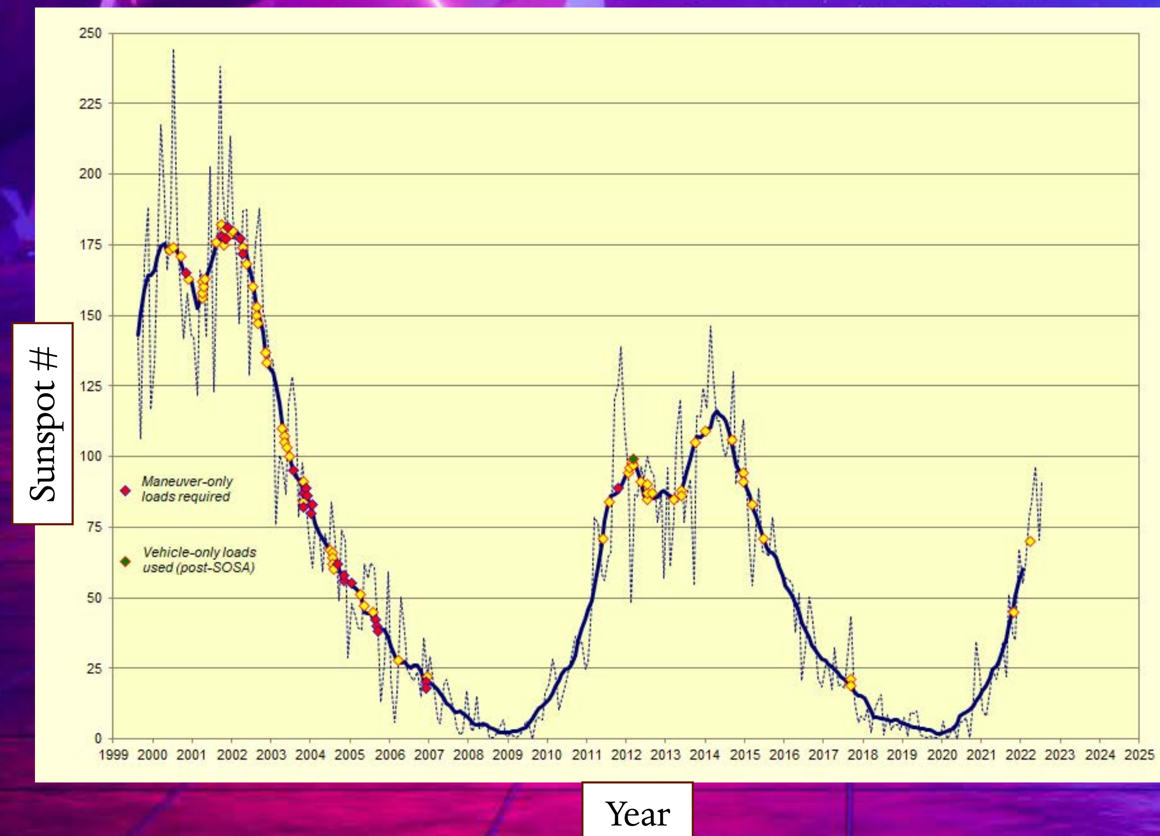


NOW	268/0233z	ACE fluence	1.86e9	SIM-Z	92904	Obsid	28920
Cursor date	268/0240z	ACE P3 flux	34500	Pitch	148.84	SI	**ACIS-I**
Cursor delta	NOW + 0:07	HRC proxy	4164	RA	3.5701	Grating	NONE
Next comm	Mon 0425 EDT	**--- Latest values ---**		Dec	-30.4116	SI mode	TE_006E6
Delta	NOW + 5:52	ACE P3 flux	34500	Roll	4.4514	Power cmd	XTZ0000005
Station	GOLDSTONE-26	ACE 2hr avg	33975	PCAD	NPNT	CCD, FEP	4, 4
Activity	ECLIPSE	HRC proxy	4164			Vid, Clock	1, 1

Results:

Over 24.25 years:

- We have had 96 Shutdowns due to the radiation environment
  - 61 Autonomous
  - 35 Manual
  - 2/3 of these were before 2007.
  - 11 Ms of lost Science time.
    - About 1/3 of a year out of a 25-year mission….



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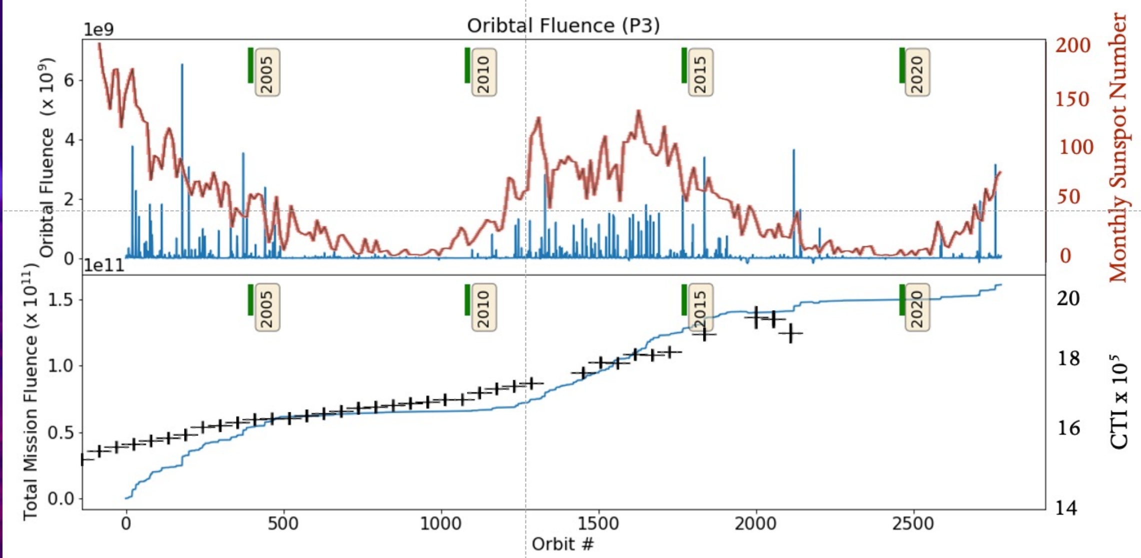

FI-CCD CTI is fair and degradation rate is within budget.
Average I-array CTI = 14.7×10^{-5}, increasing at 0.21×10^{-5}/y.
BI-CCD CTI is good and degradation rate is within budget.
Center S-array CTI = 1.7×10^{-5}, increasing at 0.13×10^{-5}/y.

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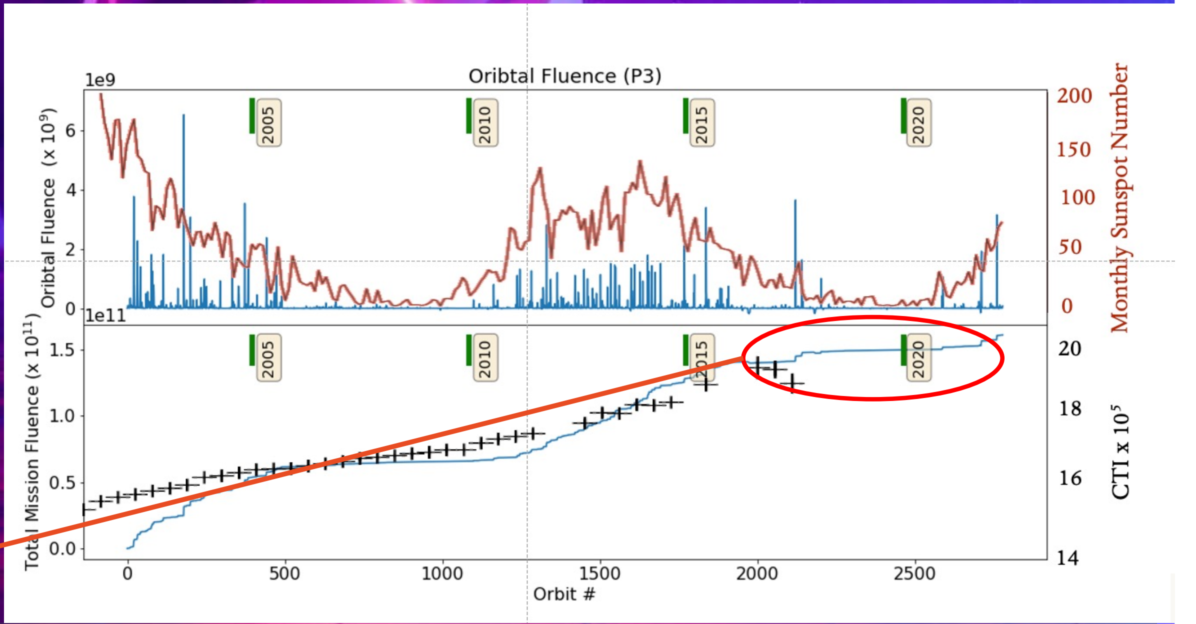

- The decay of the radioactive source used in monitoring has made tracking CTI difficult in the last 5 years.

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BI-CCD CTI is good and degradation rate is within budget.

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The Future: New Issues

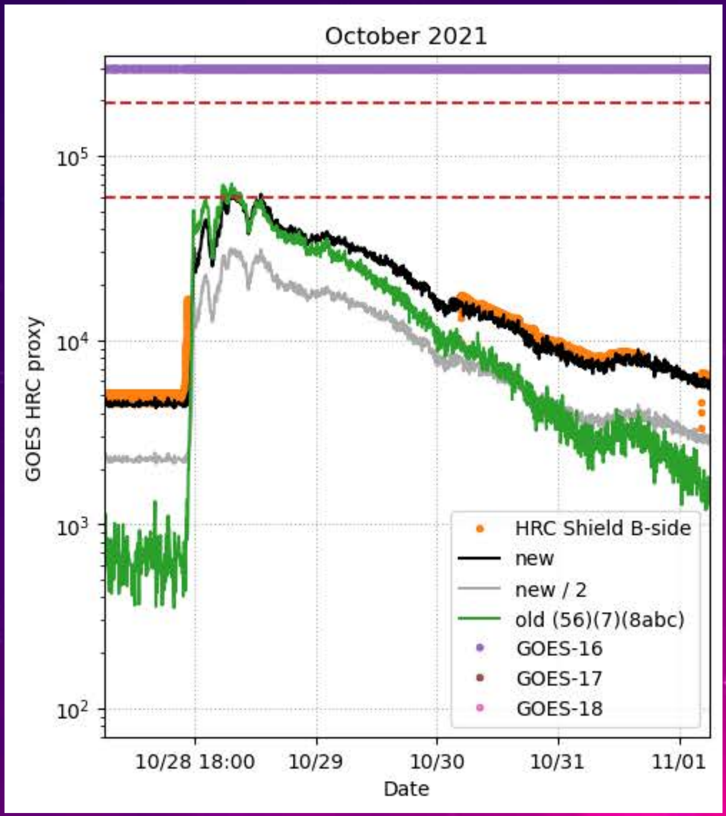
Chandra has a second detector - a High Resolution Camera, Since 2023, the Camera is only powered on when in use. Hence the background rate is only measured when it is taking data and it was removed from the safing algorithm. But,

Detector rates above 200 counts/sec/cm^2 at energies above 1 MeV will permanently degrade the detector.

The HRC high voltage must be lowered during solar storms.

The ACIS background rates are sensitive to protons < 200 keV.

We use scaled GOES rates as a proxy for the HRC shield.



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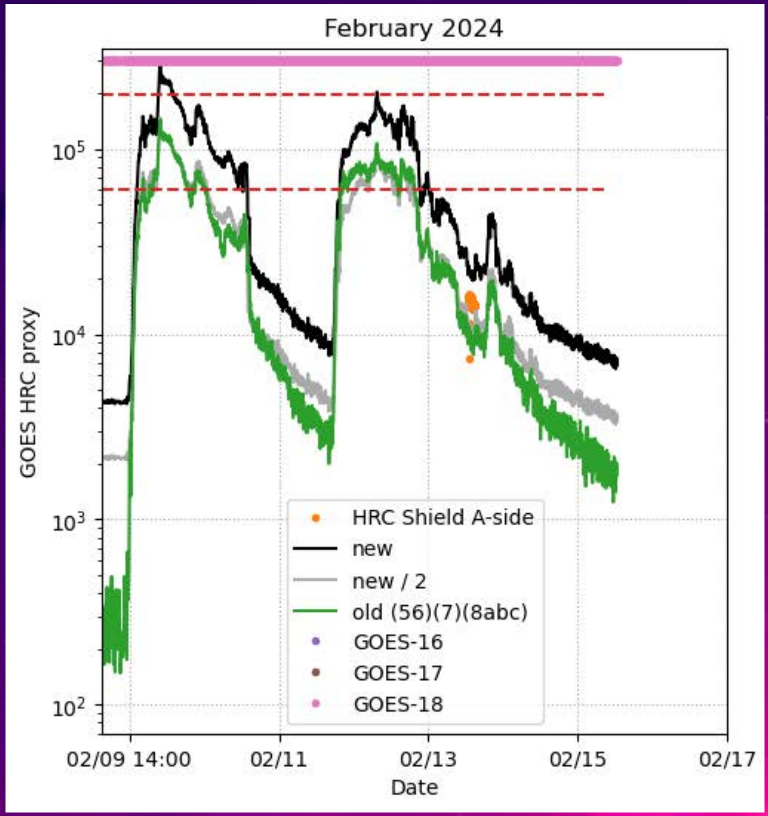
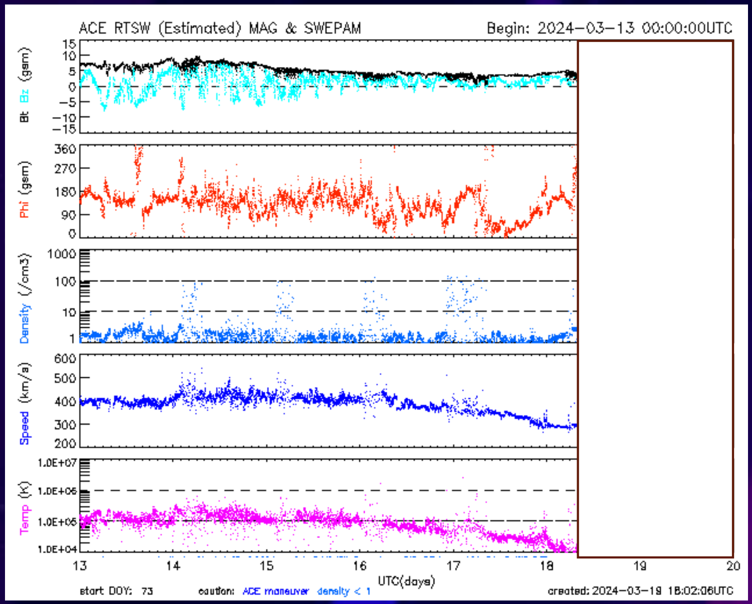
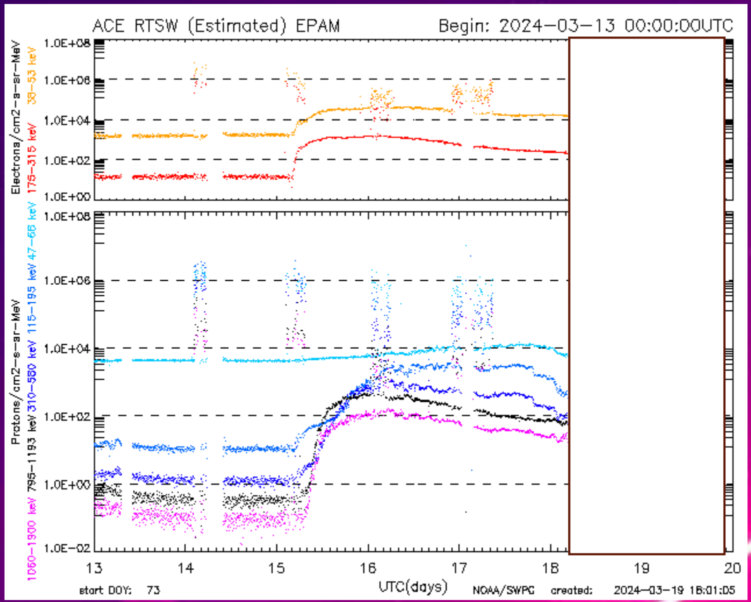


The Future: New Capabilities

- The goal is to build a tool that would help guide Chandra operations at the time of increased risk to science instruments due to Solar storms
- Use available realtimes Data GOES/ACE/SOH
- Forecast if and when actions should be taken to perform a manual shut down of science operations
- Training/validation data 27 years of combined ACE/GOES/SOHO data
    - But only 100-200 “events”





The Future: New Capabilities

- The goal is to build a tool that would help guide Chandra operations at the time of increased risk to science instruments due to Solar storms
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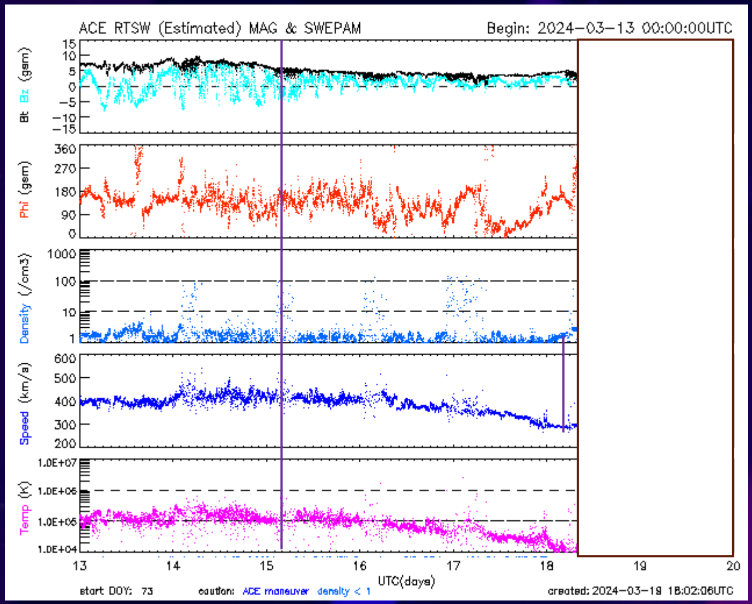

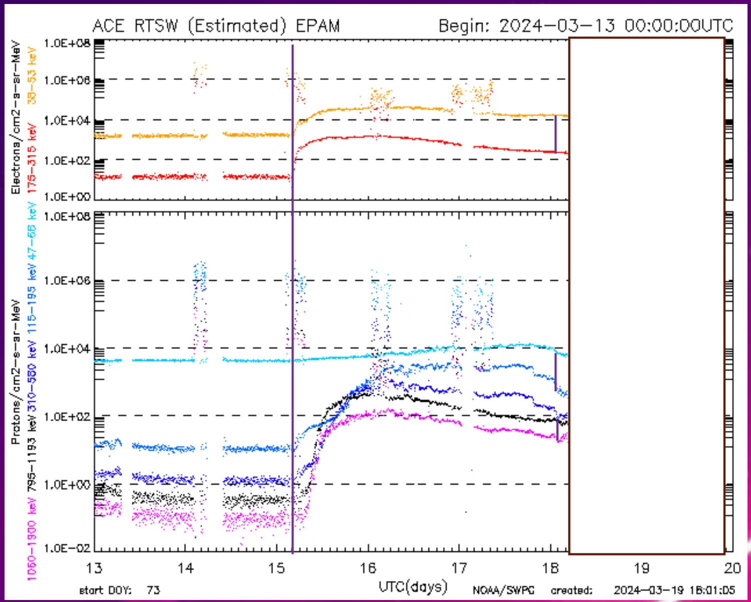

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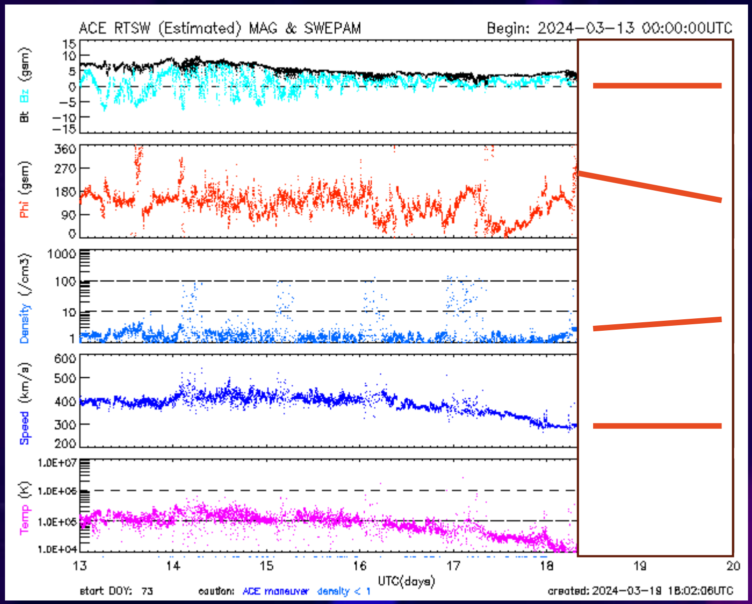

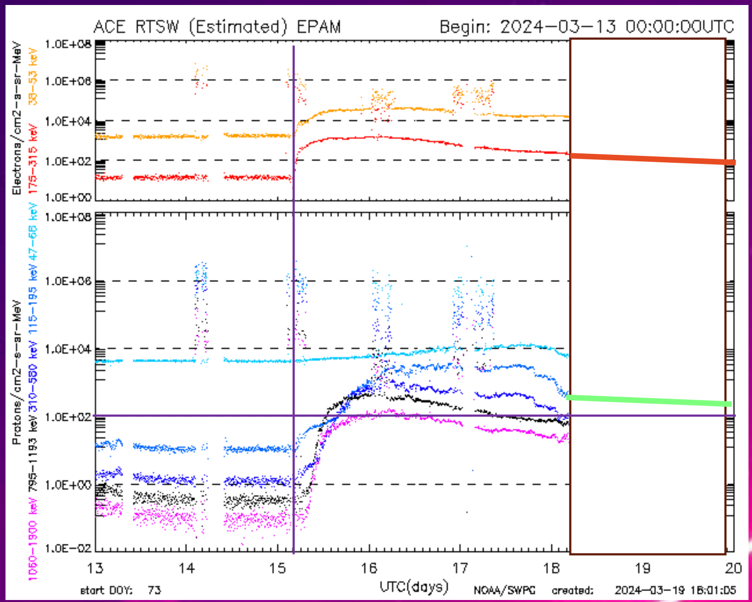

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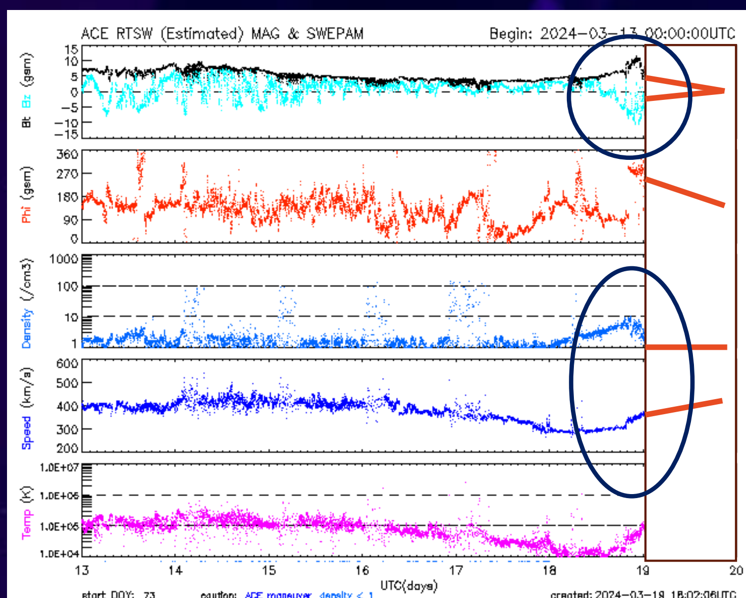

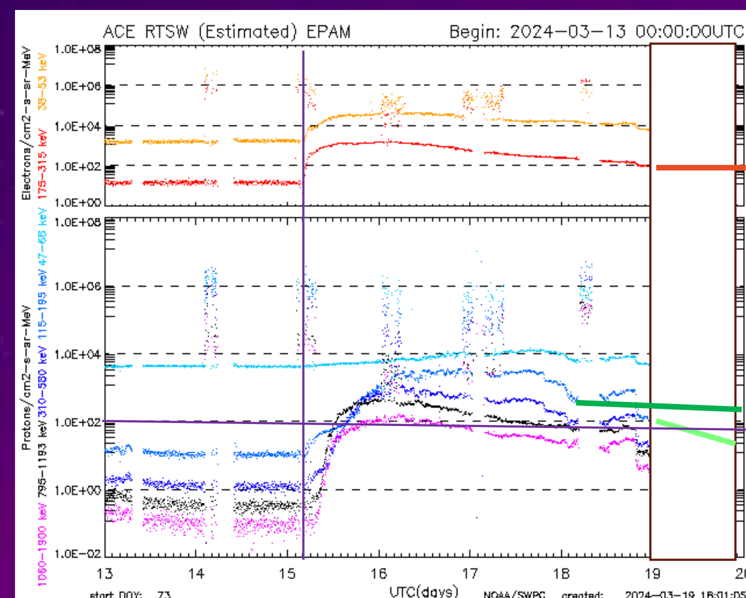

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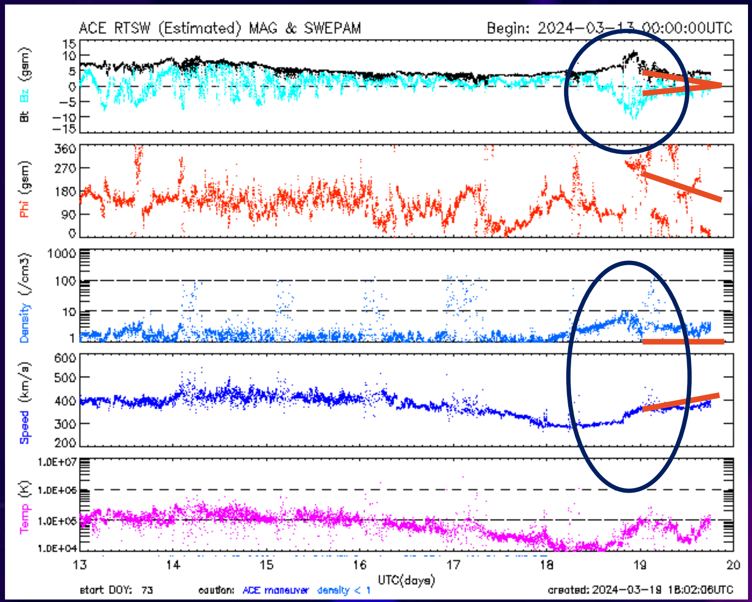
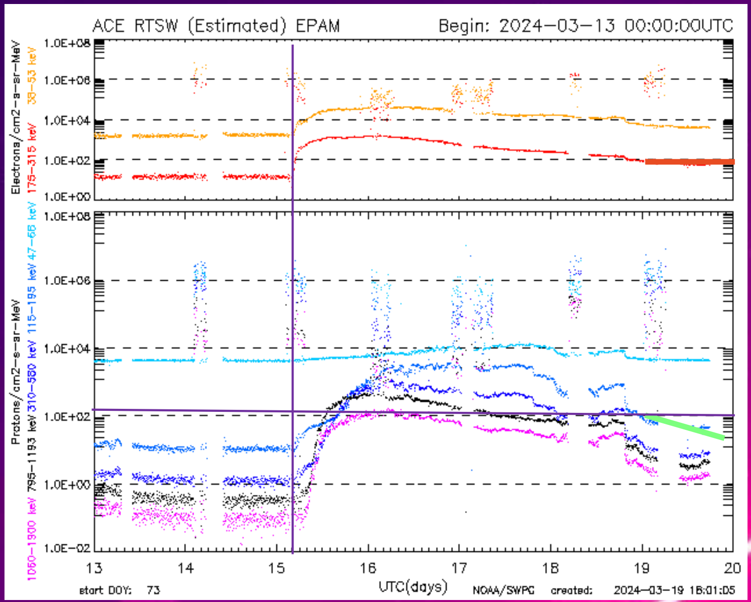
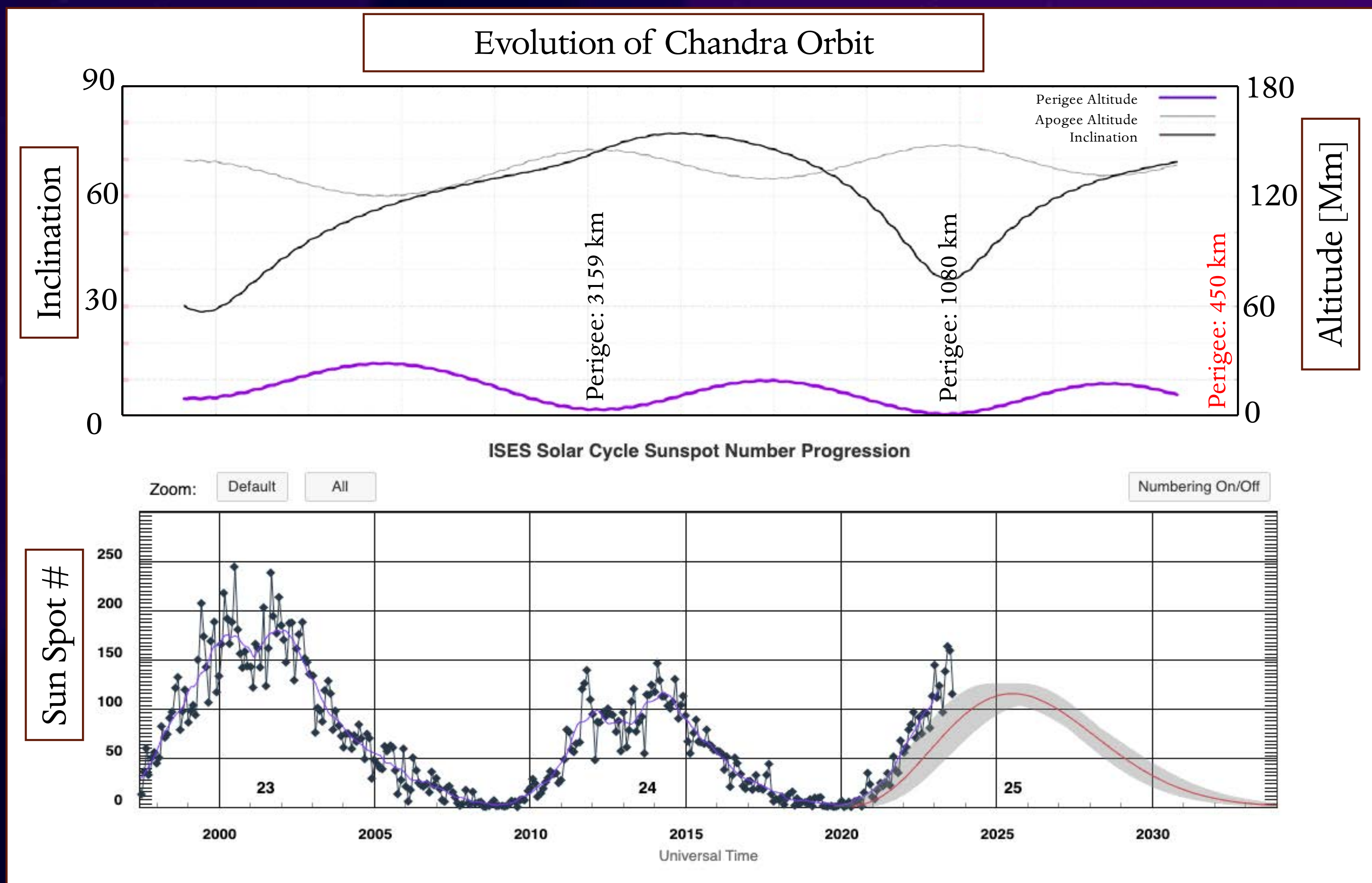




The Future: An Evolving Orbit



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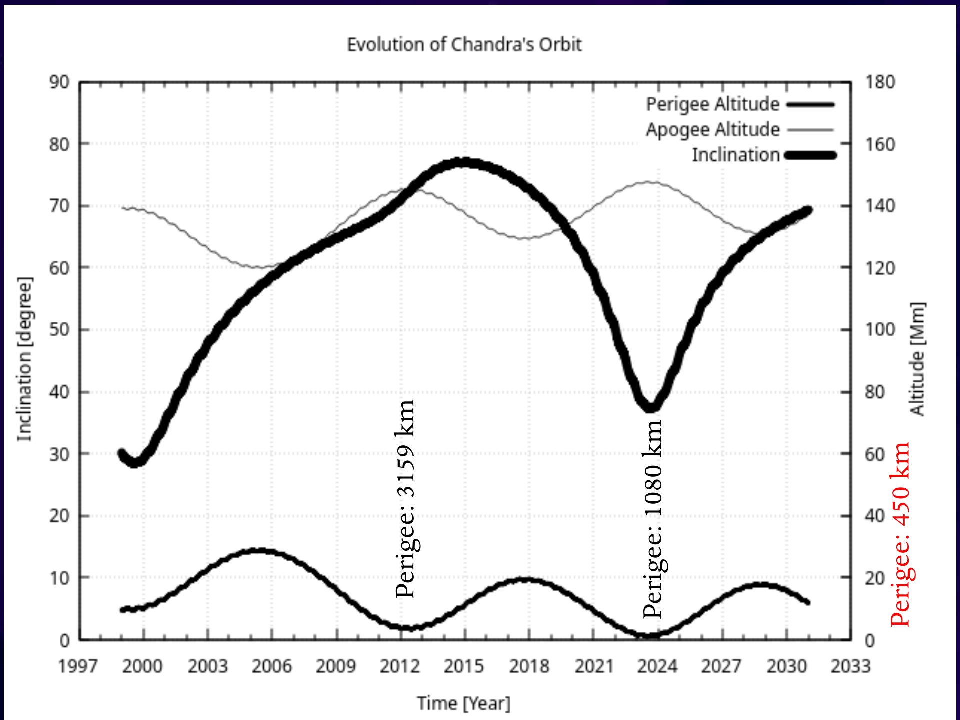
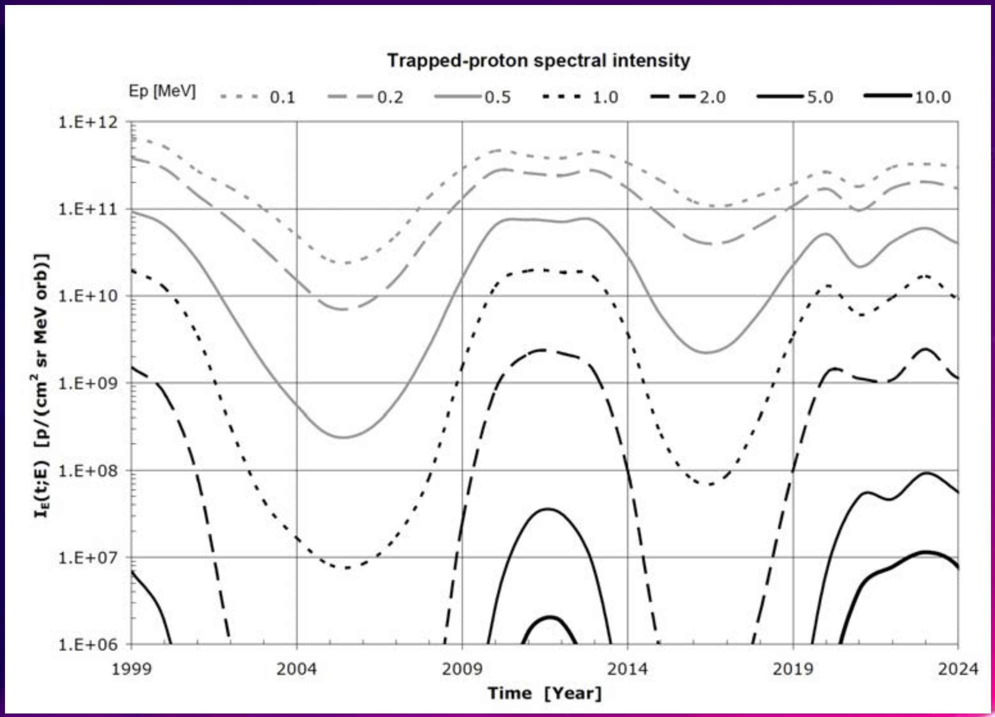
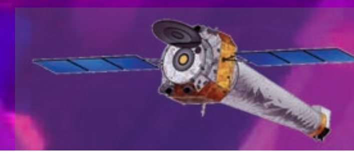
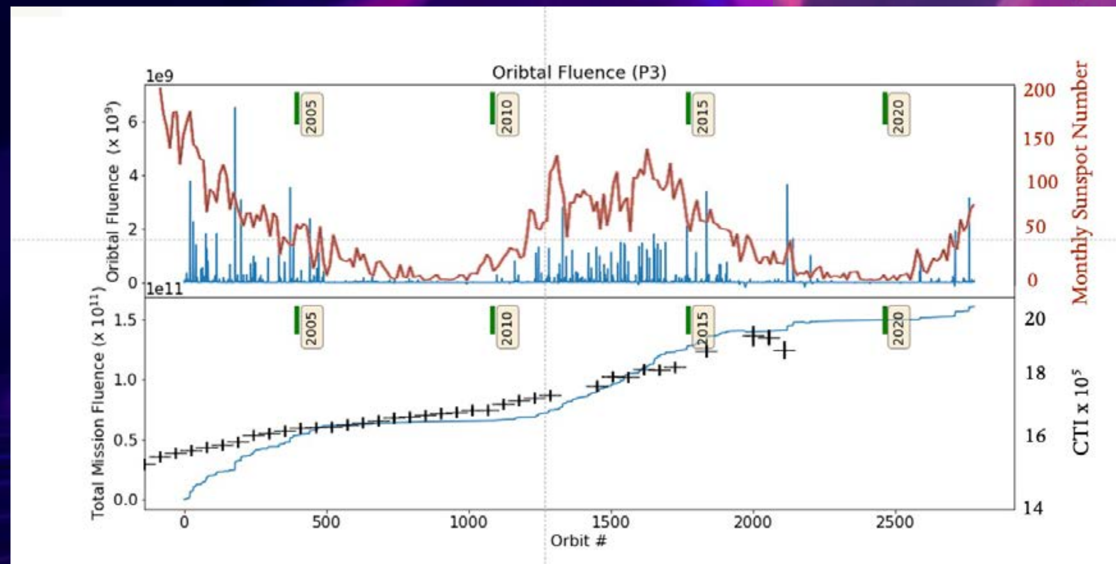




Summary



- Identified cause of ACIS CTI anomaly.
  - Soft protons scatter off X-ray mirrors into the focal plane.
  - Protons reaching the buried channel cause displacement damage.
- Stopped rapid degradation of ACIS front-illuminated CCDs.
  1. Protect ACIS during radiation belt passes: Mostly unchanged
  - Implemented strategy to control degradation outside belts.
  2. Employ autonomous intervention:
     - Now highly limited.
  3. Ground intervention uses a series of tools, under constant revision.



IT HAS WORKED:

Radiation-degradation management preserves the utility of CCDs.

FI-CCD CTI is fair, and the degradation rate is < 1.5% per year.

Average I-array CTI = 14.7×10^{-5}, increasing at 0.21×10^{-5}/y.

BI-CCD CTI is good, and the degradation rate is < 8% per year.

Center S-array CTI = 1.7×10^{-5}, increasing at 0.13×10^{-5}/y.

25 Years of Radiation Protection of the Chandra X-ray Observatory.

Thank You

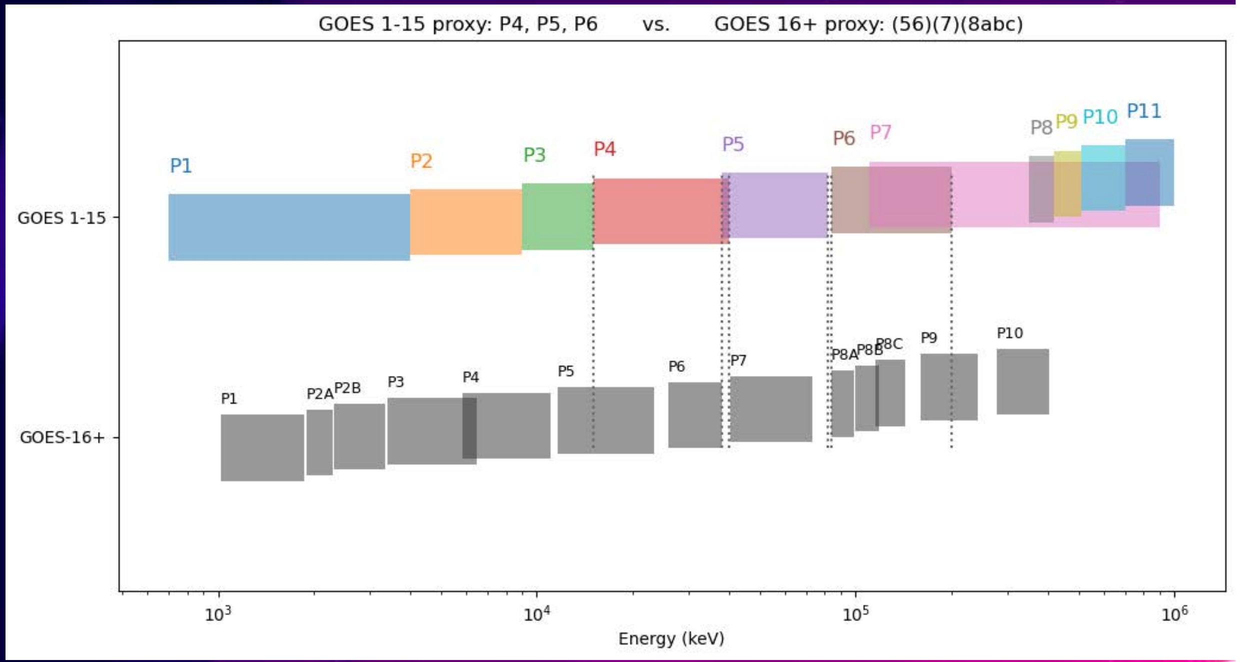
Scott Wolk
(Smithsonian Astrophysical Observatory)

Steve O'Dell, Bill Blackwell, Rob Cameron, Catherine Grant, Joe Minow, Doug Swartz, Bev. LaMarr, M. W. Bautz, Tom Aldcroft, Sabina Bucher, Jon Chappell, Joe DePasquale, Mike Juda, Eric Martin, Steve Murray, Paul Plucinsky, Dan Schwartz, Dan Shropshire, Brad Spitzbart, Paul Viens, Shanil Varani

The Future: GOES Proxy

```
df['p56'] = combine_rates_h5(df, ('p5', 'p6'))
df['p8abc'] = combine_rates_h5(df, ('p8a', 'p8b', 'p8c'))
df['p8abc9'] = combine_rates_h5(df, ('p8a', 'p8b', 'p8c', 'p9'))
```

```
def calc_old_proxy(bands): """ """
C1 = 6000 C2 = 270000 C3 = 100000
return C1 * bands[0] + C2 * bands[1] +
        C3 * bands[2]
```




```
def calc_new_proxy(bands): """ """
A1 = 143 A2 = 64738 A3 = 162505 B = 4127
return A1 * bands[0] + A2 * bands[1] + A3 * bands[2] + B
```

Summary

- Identified cause of ACIS CTI anomaly.
  - Soft protons scatter off x-ray mirrors into focal plane.
  - Protons reaching buried channel cause displacement damage.
- Stopped rapid degradation of ACIS front-illuminated CCDs.
  - Hide ACIS in NIL position during radiation-belt passes.
  - Lowered CCD temperature to –120 °C, reducing FI-CCD CTI.
- Implemented strategy to control degradation outside belts.
  - Employ autonomous, intervening, and scheduled protection.
    - Developed tools to estimate soft-proton flux throughout orbit.
- Radiation-degradation management preserves utility of CCDs.
  - FI-CCD CTI is fair and degradation rate is within budget.
    - Average I-array CTI = $14.7\text{x}10^{-5}$, increasing at $0.21\text{x}10^{-5}$/y.
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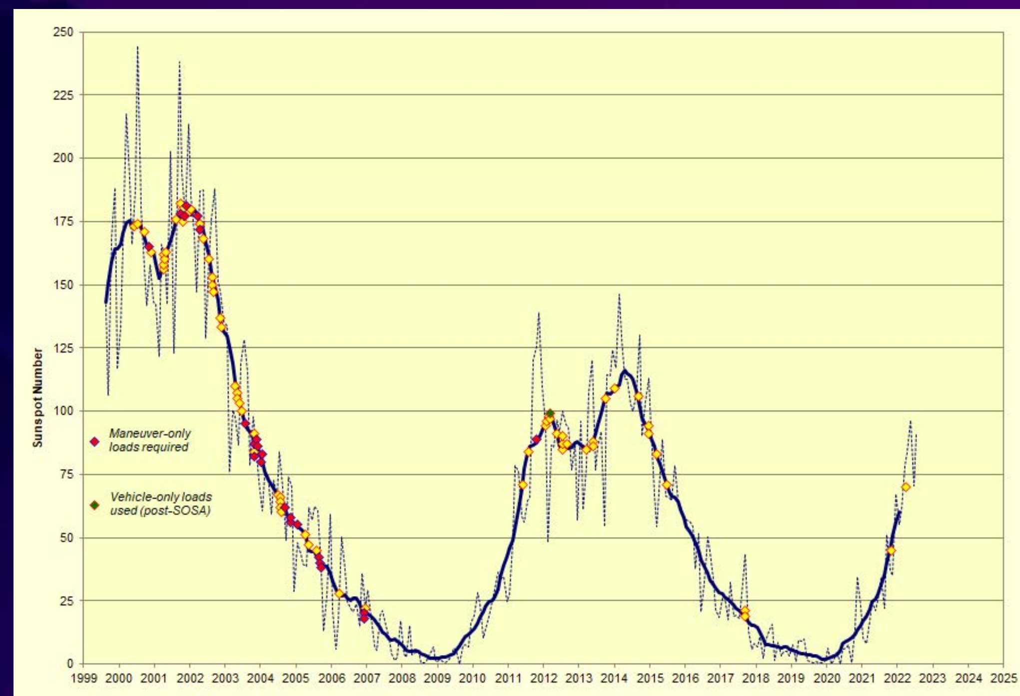

Timeline / challenges / issue

1996 Iephin (the SOHO spare) was added to monitor for HARD radiation events which could damage electronics

1998 Mission profile is designed to minimize SIM moves and keep ACIS at the aimpoint as much as possible.

1999 July Chandra Launched

1999 September: it was discovered that the spectral resolution on the ACIS CCDs was degrading rapidly

It was quickly determined that we were losing resolution due to SOFT protons getting trapped in the CCD substrate during passages through the Van Allen belts.

We immediately implemented an operational change to prevent ACIS from being exposed to the radiation belts, but preventing further damage from soft protons above the belts would require a completely new apparatus

Summary

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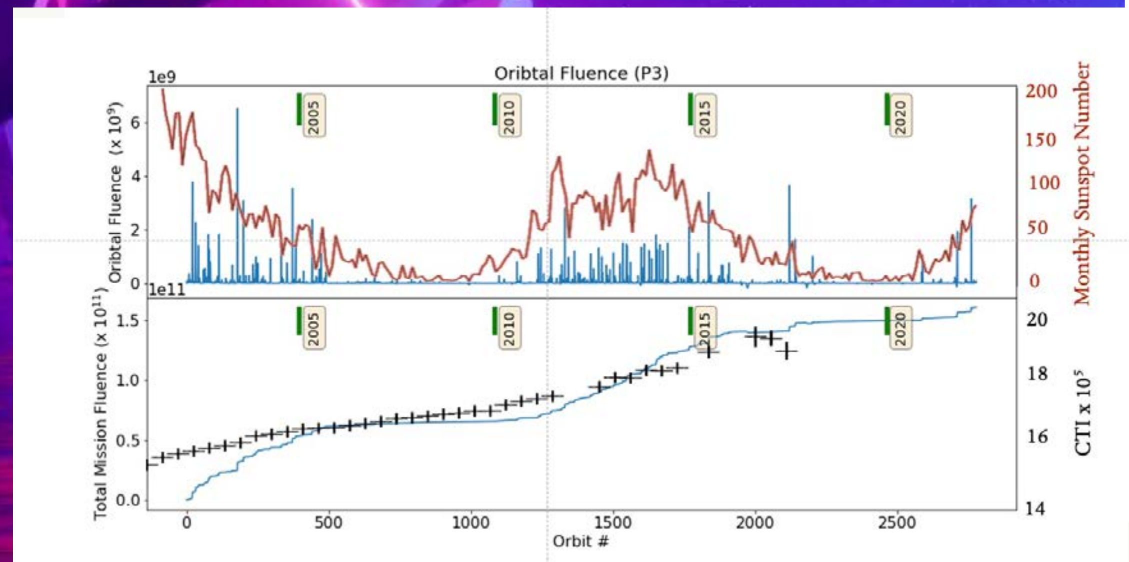

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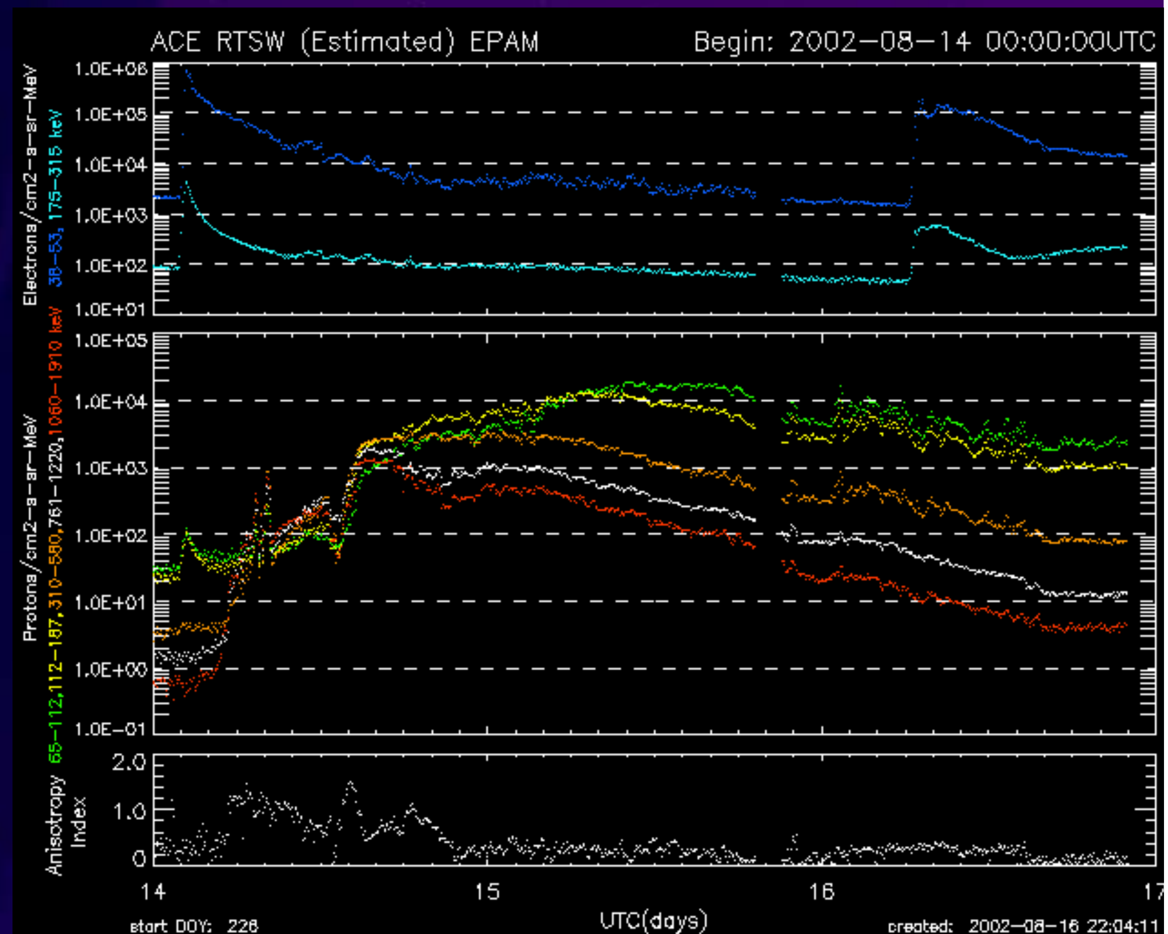
Real-time environment

- Chandra radiation-monitor real-time data during DSN contacts
  - Nominally 3 1-h DSN contacts/d
  - Not sensitive to lower-energy (< 4 MeV) protons
- • NOAA Space Environment Center (SEC) provides real-time data
  - Space-environment data Updated at 1- or 5-min intervals
  - NOAA's Geostationary Operational Environmental Satellites
    - GOES X-ray, energetic proton & electron detectors; magnetometer
  - NASA's Advanced Composition Explorer (ACE)
    - In L1 orbit, 0.01-AU sunward (solar-wind upstream)
    - Relevant ACE instruments
      - Solar Isotope Spectrometer (SIS) ! hard protons
      - Electron, Proton, Alpha Monitor (EPAM) ! suprathermal ions
      - Magnetometer & Solar-Wind EPAM ! thermal plasma and field
- MAG-SWEPAM-driven predictor of geomagnetic activity (Kp)

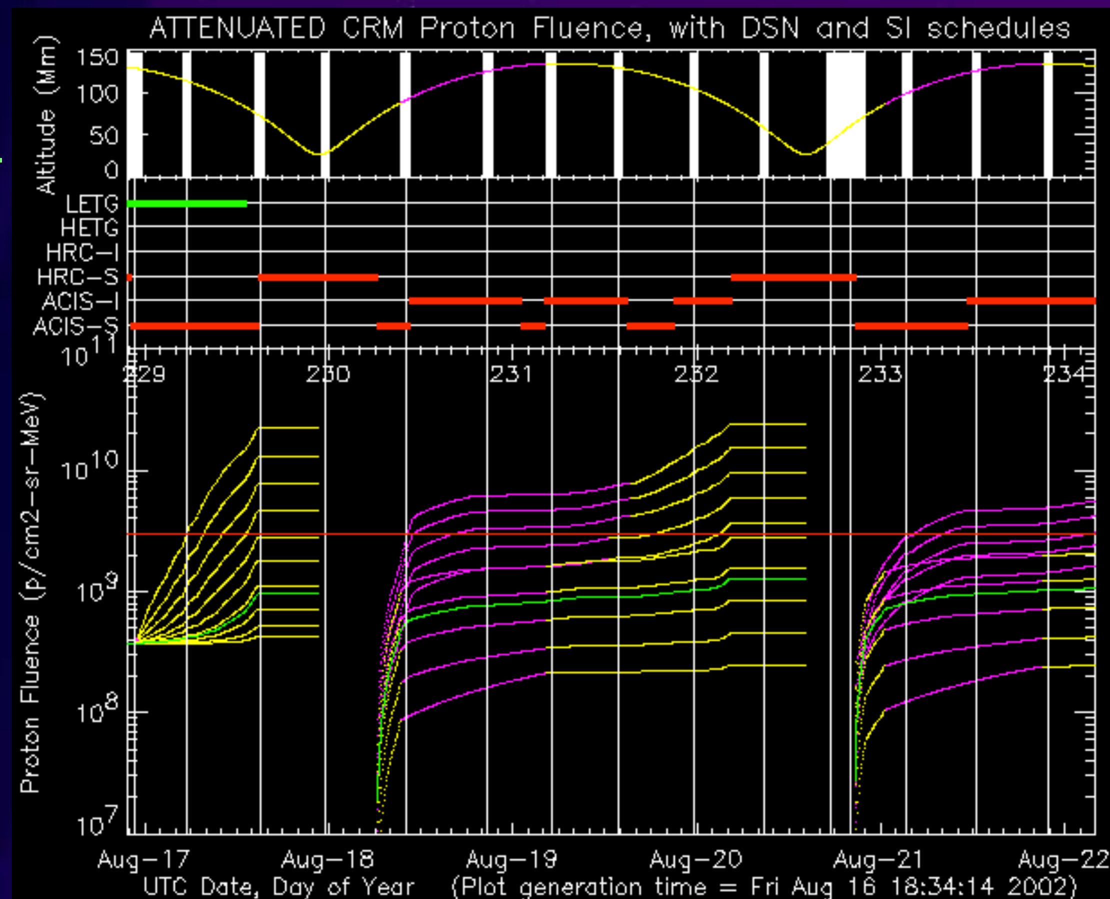
ACE EPAM soft protons

- NOAA SEC data
  - RT soft protons
  - RT soft electrons
- Use for Chandra
  - Real-time proton environment
    - All for solar wind
    - Partial for magnetosheath & magnetosphere
  - Damaging protons
    - EPAM-P3 channel 0.14-MeV protons
    - CXC alert if fluence high



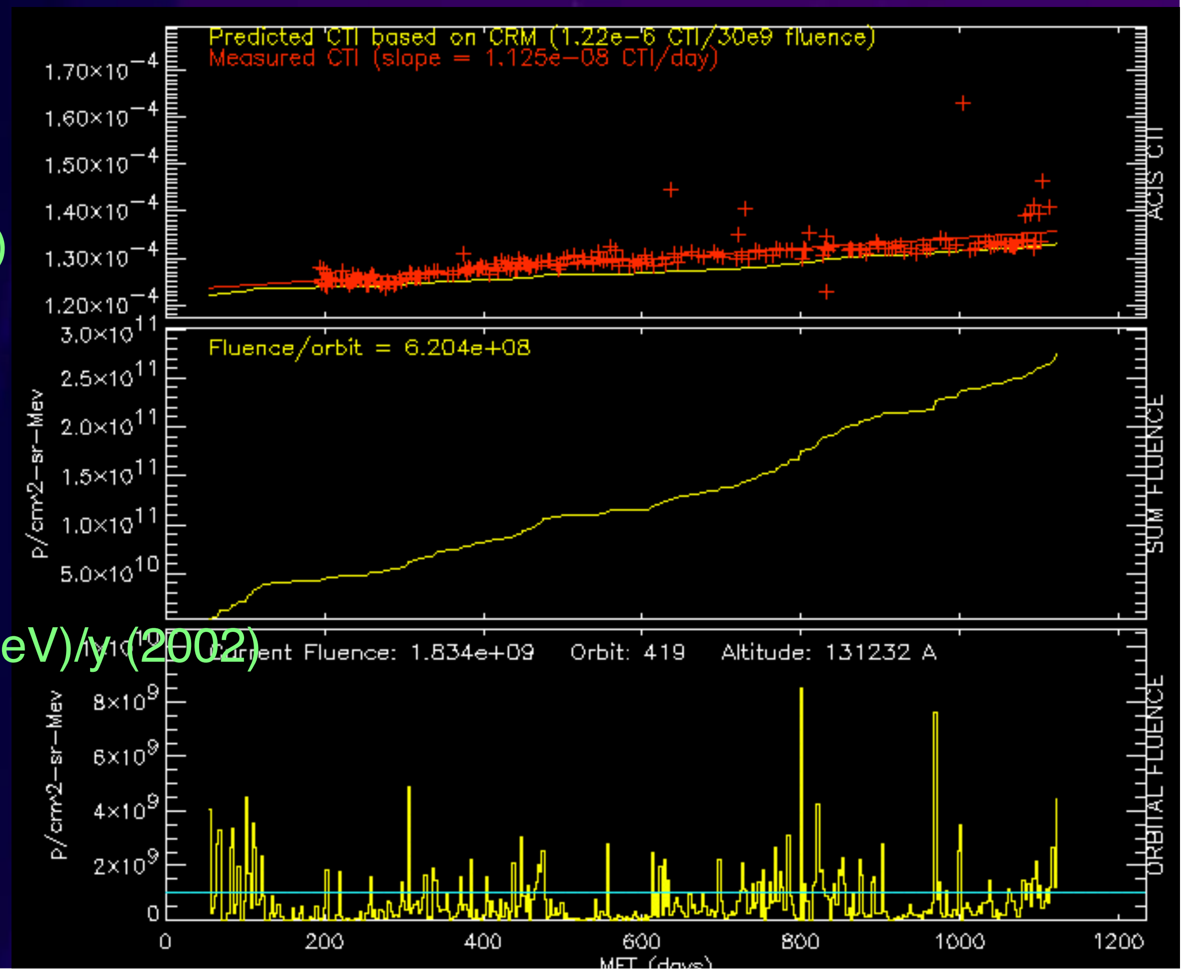
Real-time CRM Estimator

- Inputs
  - ACE EPAM P3 ⇒ solar-wind 0.14-MeV-p flux
  - ACE MAG/SWEPAM ⇒ Kp
    - Kp + CRM ⇒ magnetospheric 0.14-MeV-p flux
  - Chandra config.⇒ transmission
    - HRC: 0
    - HETG-ACIS: 0.2
    - LETG-ACIS: 0.5
    - Bare ACIS: 1



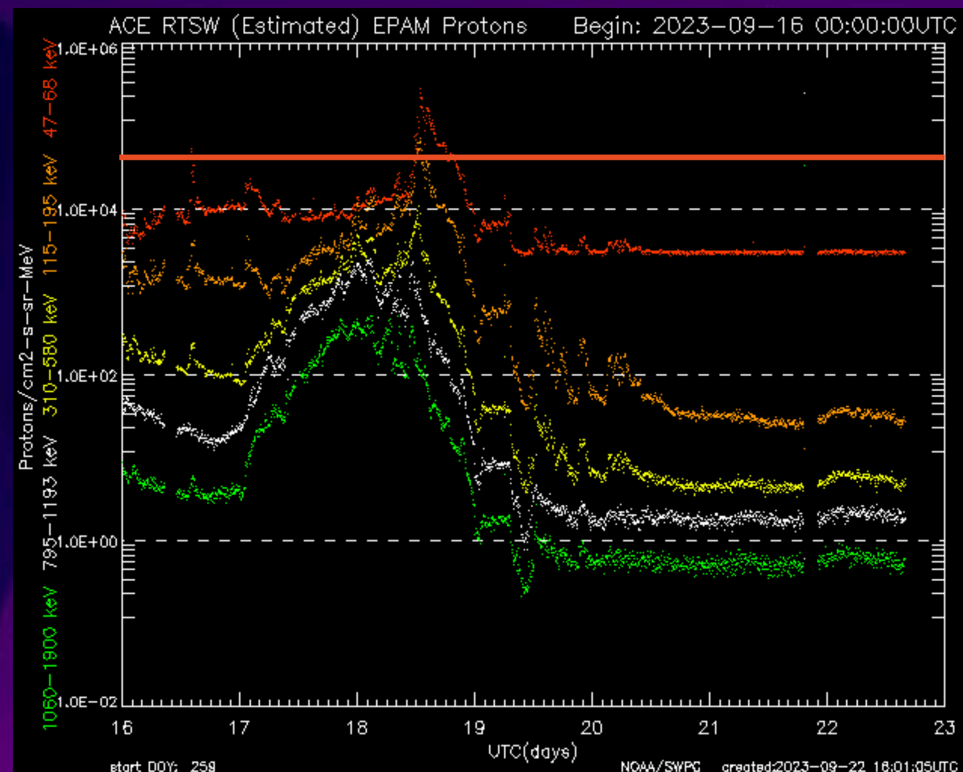
FI CCD CTI Status

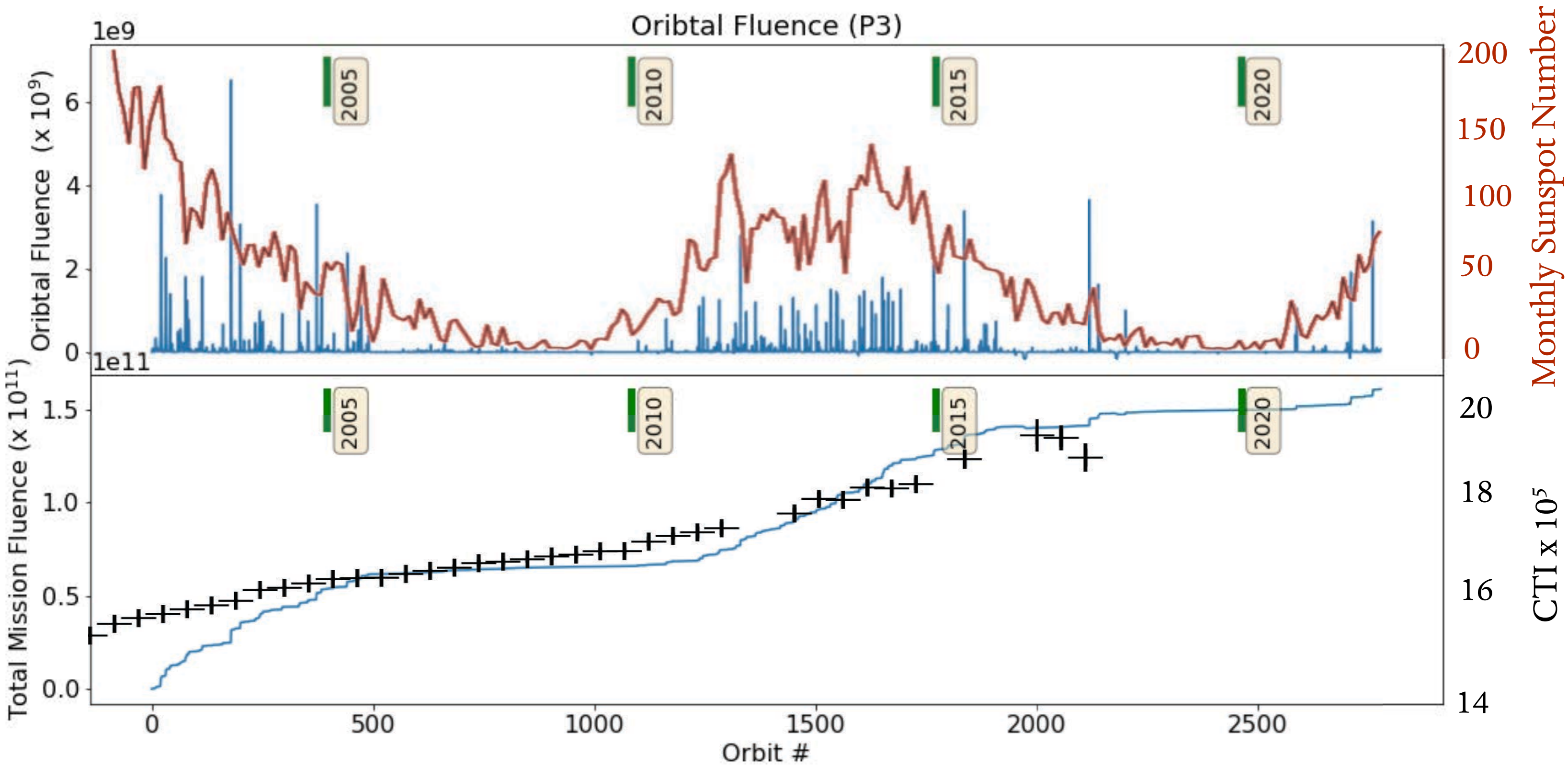
- Initial degradation
  - ΔCTI=12×10^{-5}
  - 3×10^{12} 0.14-MeV p/(cm2 sr MeV)
    - 8 rad-belt passes
    - AP-8 environment
  - 4×10^{-17}/AP8-fluence
- • Ensuing degradation
  - dCTI/dt=0.4×10^{-5}/yr
  - 0.09×10^{12} 0.14-MeV p/(cm2 sr MeV)/y (2002)
    - Rad-belt protected
    - CRM environment
  - 5×10^{-17}/CRM-fluence



Mitigation Strategies: Commanded Intervention

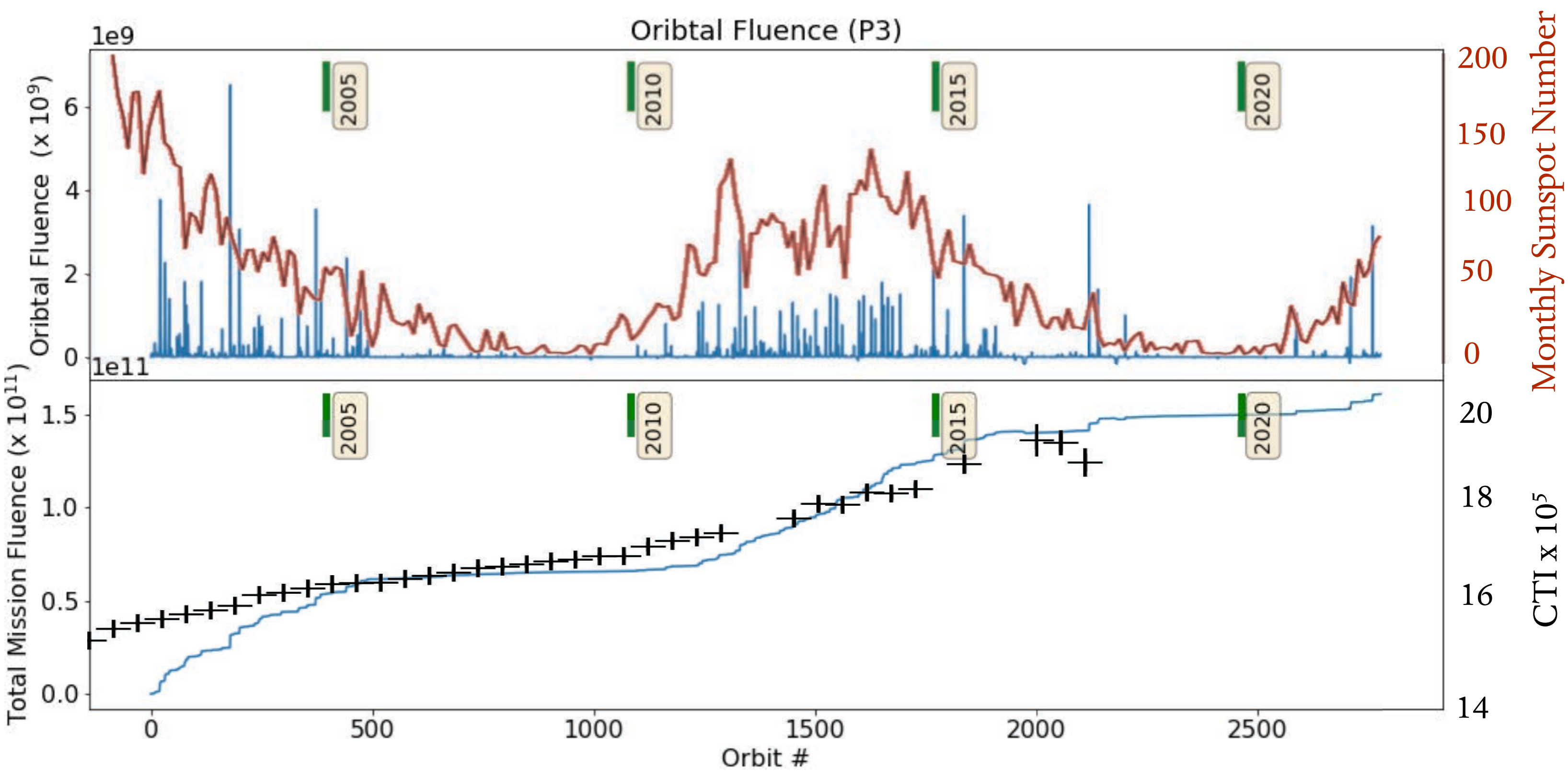
- Monitor the estimated soft-proton environment in Chandra’s orbit.
  - ACE (launched in 1999) is the only spacecraft we are aware of that directly monitors the relevant protons.
  - Developed model for the entire Chandra soft-proton environment.
  - Use real-time space-environment data to drive the model.
- When needed, halt load and command ACIS to a safe position.
  - Typically wait for DSN contact.
  - Since 2011 science loads are halted but spacecraft maneuvers continue.





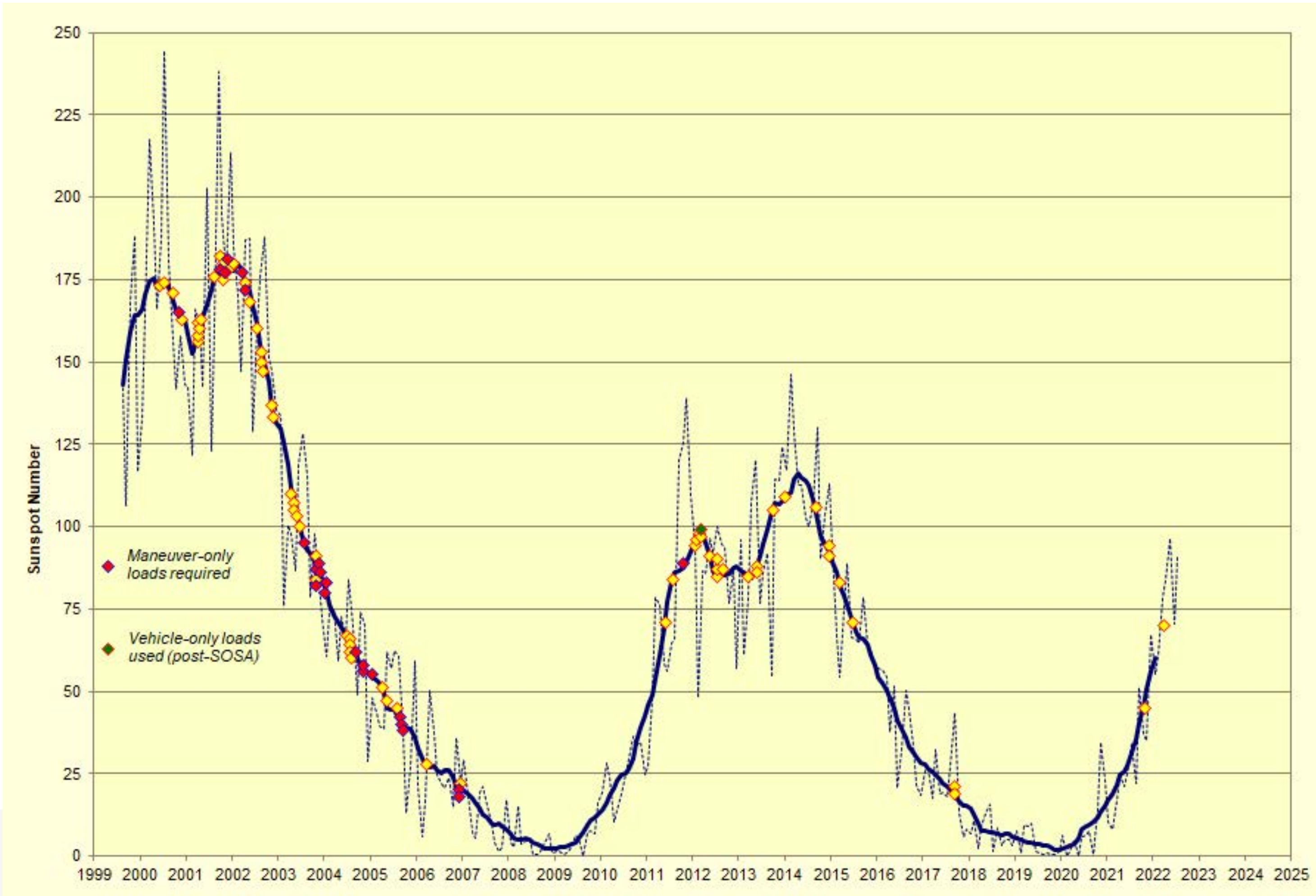
Oribtal Fluence (P3)
1e9
Oribtal Fluence (x 10^9)
0
2
4
6
2005
2010
2015
2020
200
150
100
50
0
Monthly Sunspot Number
1e11
Total Mission Fluence (x 10^11)
0.0
0.5
1.0
1.5
20
18
16
14
CTI x 10^5
0
500
1000
1500
2000
2500
Orbit #

FI CCD CTI Status

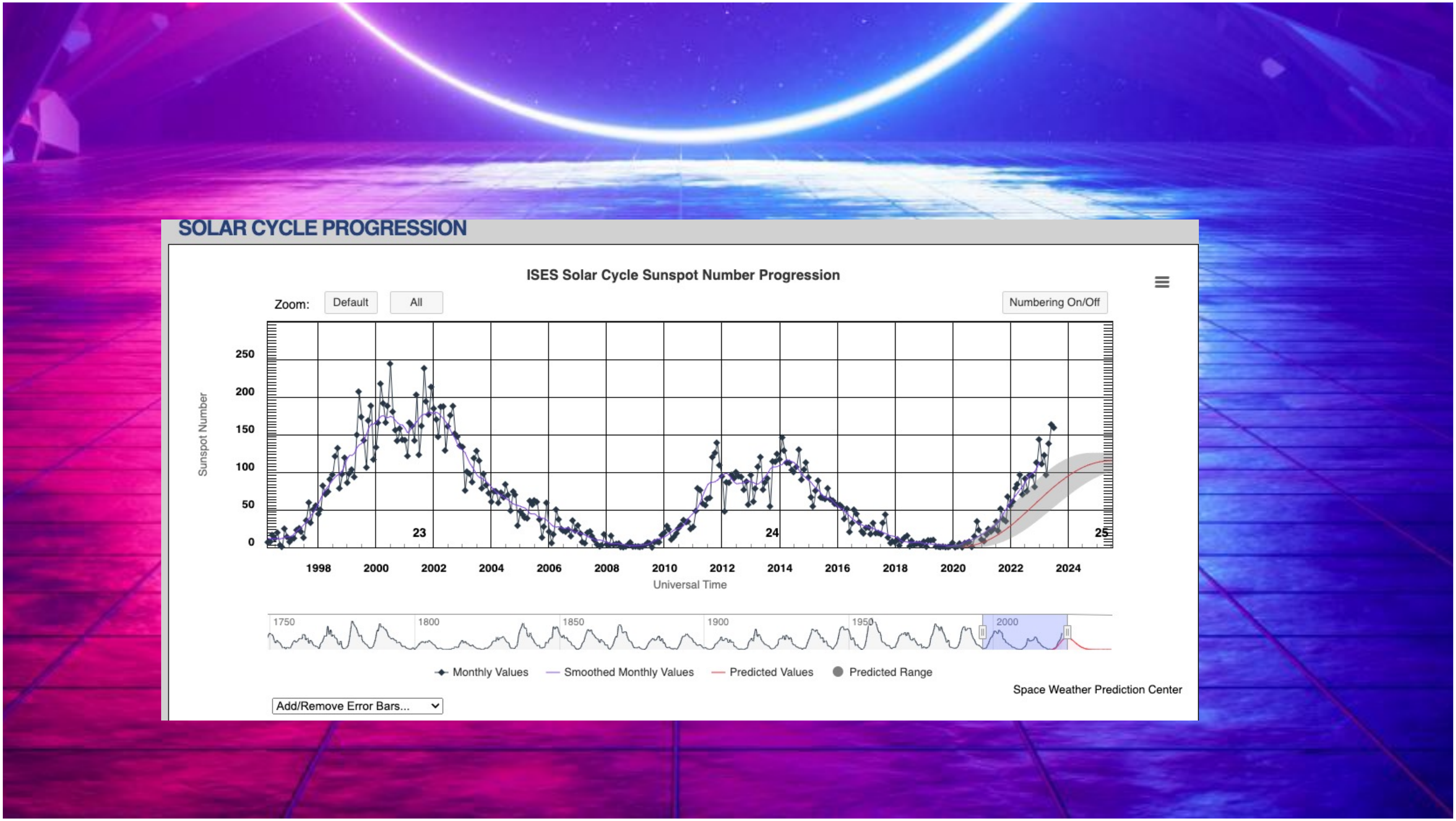


Space based monitoring

- ACE P3 has been our primary monitor of the affecting protons.
  - As far as we know this is the only spaceborn monitor at this energy
  - Full-time ACE RT support ended ~ July 2015 in favor of DSCOVR
  - NOAA has maintained about 21-hour support since that time.
  - ACE will run out of fuel in the 2026-2028 time frame.
- GOES ~1-3 MeV and ~3-10 MeV have been mapped to Ephin channels and appropriate proxy alerts are set up.
  - GOES has gone through several iterations during the Chandra mission
  - We started with monitoring of GOES-8



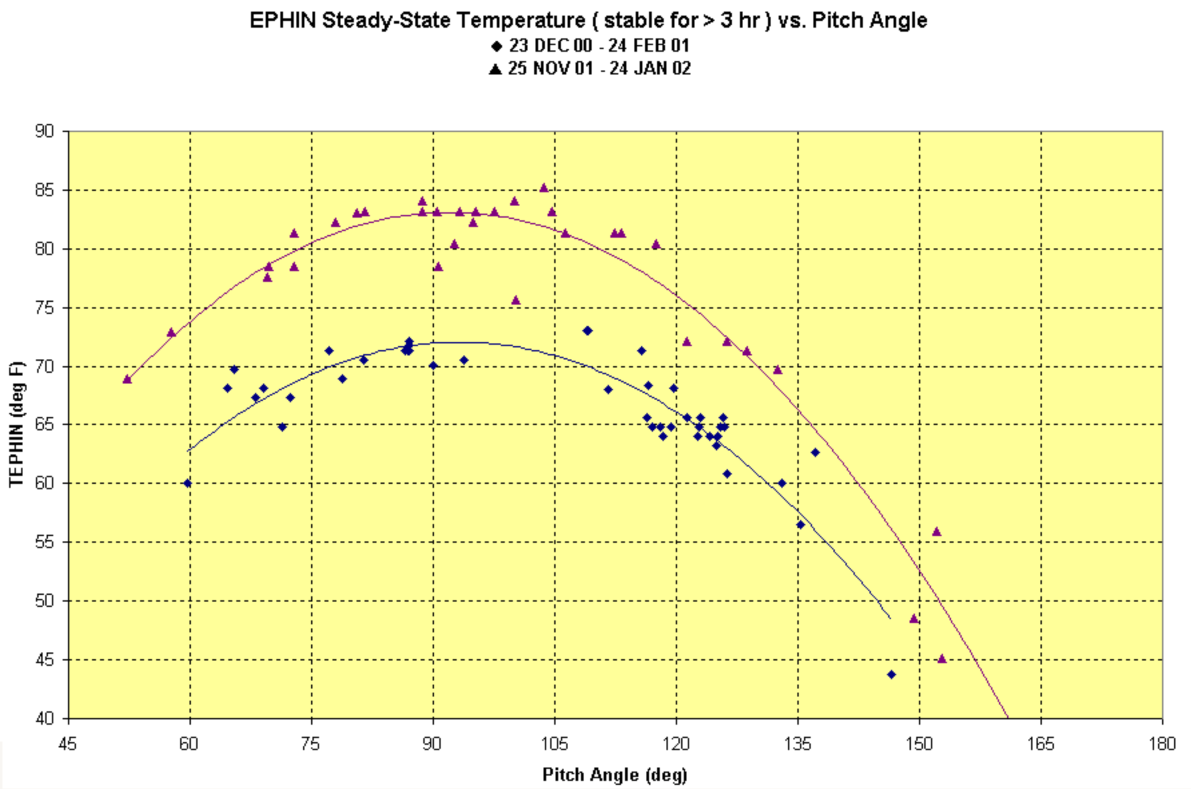
Sunspot Number
250
225
200
175
150
125
100
75
50
25
0
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Maneuver-only loads required
Vehicle-only loads used (post-SOSA)



SOLAR CYCLE PROGRESSION
ISES Solar Cycle Sunspot Number Progression
Zoom:
Default
All
Numbering On/Off
Sunspot Number
250
200
150
100
50
0
23
24
25
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
Universal Time
1750
1800
1850
1900
1950
2000
Monthly Values
Smoothed Monthly Values
Predicted Values
Predicted Range
Space Weather Prediction Center
Add/Remove Error Bars...

EPHIN

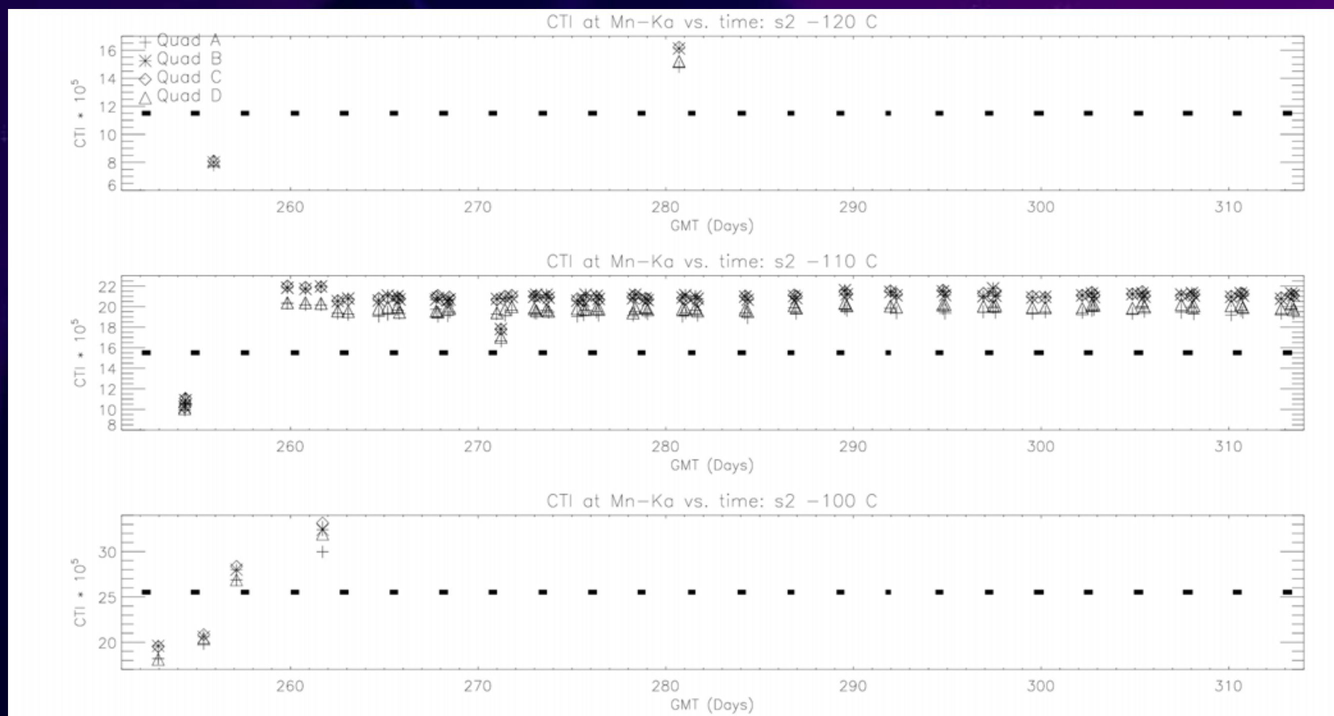
- EPHIN Temperature versus Pitch Angle



Data Generated by Rino Giordano, the FOT thermal engineer

FI-CCD CTI degradation

- Charge transfer inefficiency (CTI) of front-illuminated (FI) CCDs
  Rapid increase in CTI (4×10^{-5}/orbit @ -100 °C) after first light



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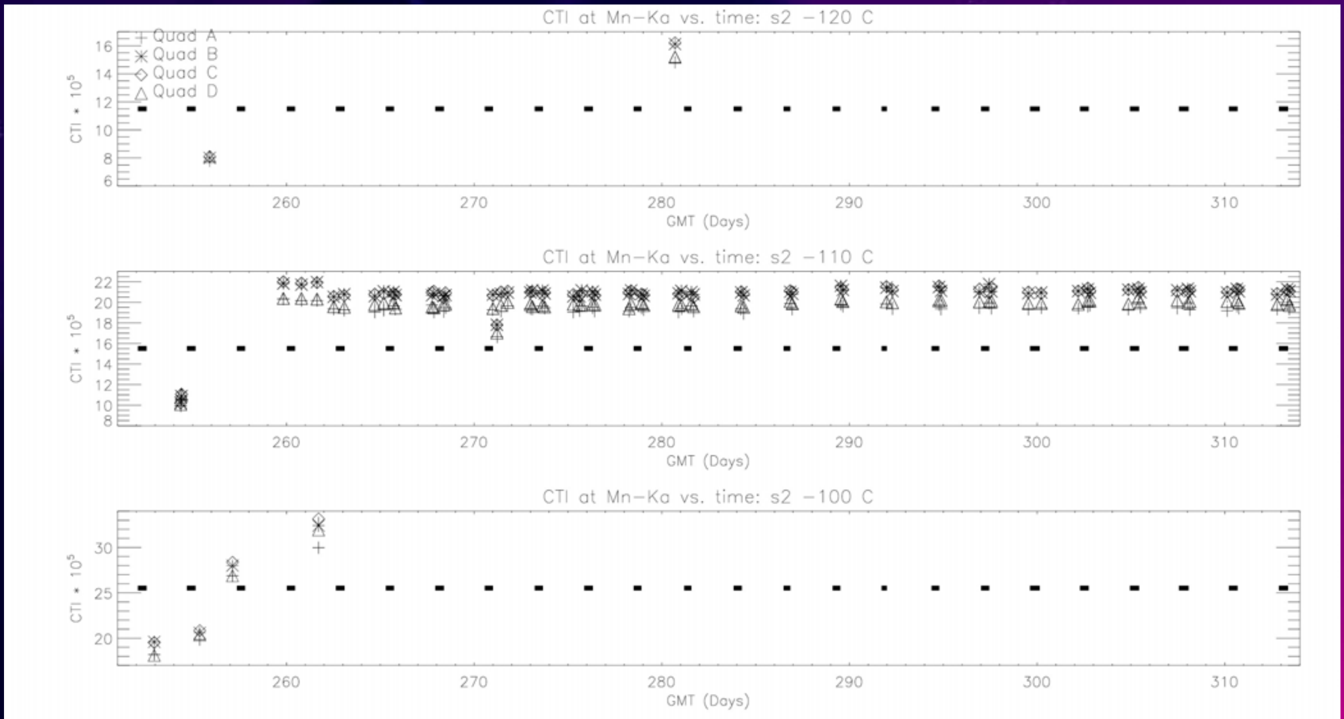

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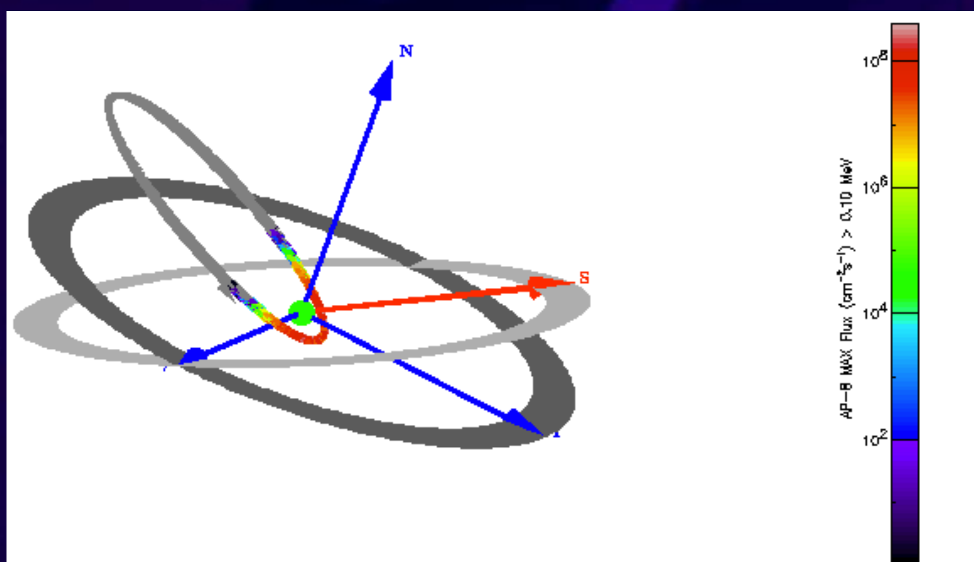
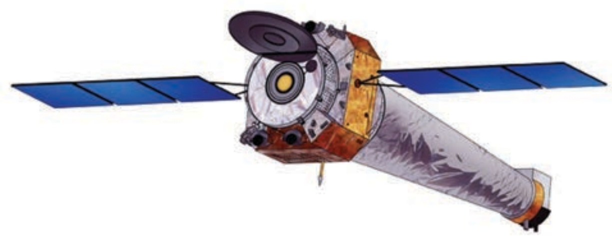
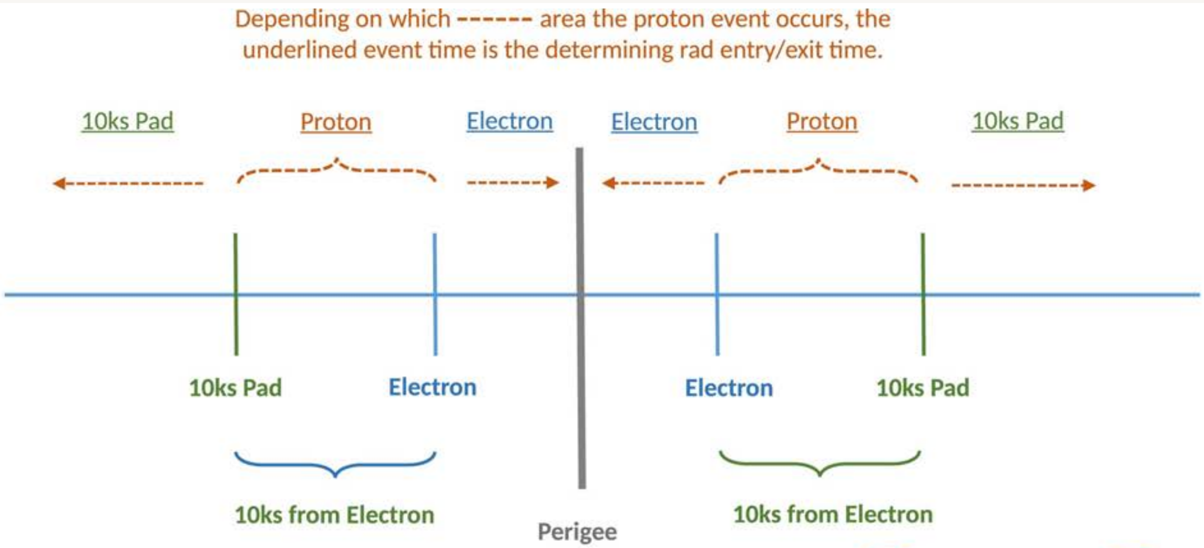
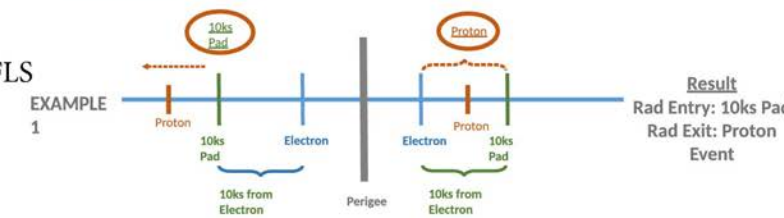








The mission planning team determines the radiation zones based on the OFLS Orbit Events for CRM protons (QF013M) and AE8 electrons (EF1000).

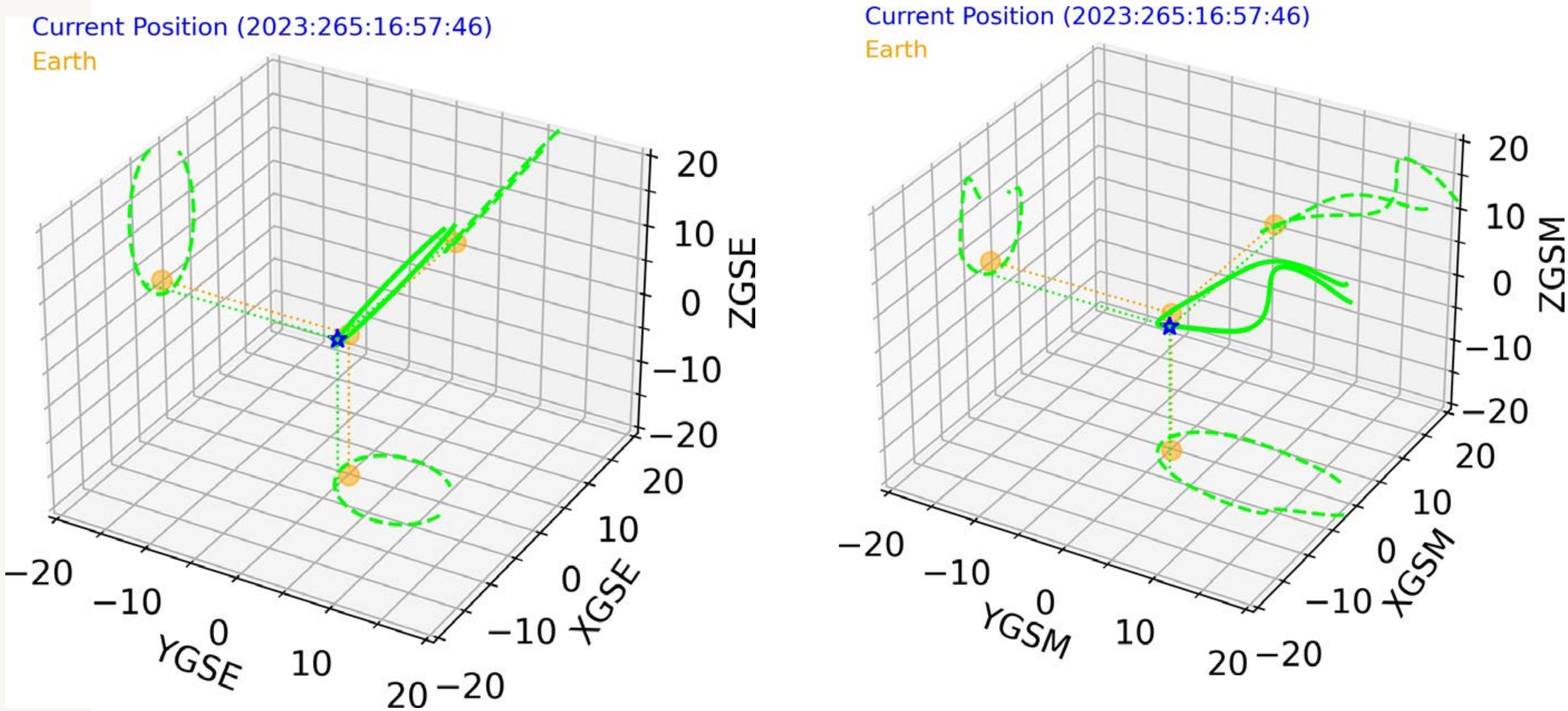


Entry:

- If the proton entry event occurs after the electron entry event, then the electron entry event starts the radiation zone.
- If the proton entry event occurs less than 10ks prior to the electron entry event, then the proton entry event starts the radiation zone.
- If the proton entry event occurs greater than 10ks prior to the electron entry event, then the radiation zone starts 10ks prior to the electron entry event.

Exit:

- If the proton exit event occurs before the electron exit event, then the electron exit event ends the radiation zone.
- If the proton exit event occurs less than 10ks after the electron exit event



Current Position (2023:265:16:57:46)
Earth
ZGSE
XGSE
YGSE
Current Position (2023:265:16:57:46)
Earth
ZGSM
XGSM
YGSM