# Shelter from the Storm: Protecting the Chandra X-ray Observatory from Radiation

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**Abstract.** NASA's *Chandra* X-ray Observatory was launched in July 1999, and the first images were recorded by the ACIS x-ray detector in August 1999. Shortly after first light, degradation of the energy resolution and charge transfer efficiency in the ACIS CCD detectors was observed, and this was quickly attributed to cumulative particle radiation damage in the CCDs, in particular from 100 keV to 200 keV protons.

Since the onset of this radiation damage to ACIS, several improvements have been made to autonomous *Chandra* operation and ground-based operations and mission planning, to limit the effects of radiation while preserving optimum observing efficiency for the Observatory. These changes include implementing an automatic science instrument radiation protection system on *Chandra*, implementing a real-time radiation monitoring and alert system by the Science Operations Team, and improving the radiation prediction models used in mission planning for the Observatory. These satellite-based and ground-based systems provide protection for *Chandra* from passages through the Earth's trapped radiation belts and outer magnetosphere and from flares and coronal mass ejections from the Sun.

We describe the design and performance of the automatic on-board radiation protection system on *Chandra*, and the ground-based software systems and data products for real-time radiation monitoring. We also describe the development and characterize the performance of the Chandra Radiation Model (CRM), which provides predictions of the solar-wind and magnetospheric proton fluxes along *Chandra*'s orbit, indexed by the geomagnetic activity index Kp. We compare the observed and predicted damage rates to ACIS based on net mission proton fluence, and outline planned enhancements to the CRM.

## 1. Introduction

*Chandra* is in an elliptical orbit around the Earth, with a perigee altitude of 10,000 km and an apogee altitude of 140,000 km. *Chandra*'s orbit passes through the Earth's magnetosphere and radiation belts and into the solar wind beyond the magnetosphere. Thus *Chandra* is exposed to both a continuous proton flux from the Sun, in the form of the steady solar wind, and from episodic solar flares and large Coronal Mass Ejections (CMEs), and also trapped protons in the magnetosphere and magnetosheath.

The density of damaging 100–200 keV protons in *Chandra*'s environs increases greatly ($\sim\times10^5$) in the radiation belts and throughout *Chandra*'s orbit after CME events, compared to the normal proton density during *Chandra*'s science operations, at altitudes above $\sim 70,000$ km.

After launch, it was discovered that 100–200 keV protons can reflect off *Chandra*'s x-ray optics and reach the ACIS CCD detector. These protons can cause lattice damage in the front-illuminated silicon CCDs, which results in degraded charge transfer efficiency and hence degraded energy resolution for the ACIS detector. Although significant damage occured in the early mission, the damage rate has been slowed dramatically by the following operational changes.

## 2. Radiation Protection System Components

The three principal components of the overall system for protecting *Chandra* from radiation are:

- improvements to the flight software for autonomous protection
- implementation of ground radiation monitoring operations
- the development of an improved model for predicting solar wind and magnetospheric proton fluxes in the Chandra orbit.

### 2.1. Autonomous Protection

Because the *Chandra* Operations Control Center is not continuously in communication with *Chandra*, an enhanced autonomous radiation protection system had to be added to *Chandra*'s capabilities after launch. Flight software changes were implemented in November 1999, as a new Stored Command Sequence (SCS 107) in the On-Board Computer (OBC).

Features:

- Provided an autonomous safing capability for the protection of science instruments (SIs). This does not replace scheduling of SI protection activities through perigee passages, but provides backup protection in case of schedule failures (e.g. if the mission schedule is incorrectly built or stops running).
- Extended the spacecraft safing capabilities to include safing of the SIs in the event of spacecraft failures interrupting the science mission.
- Provided better use of EPHIN (on-board radiation detector) energy ranges, for detecting low energy protons, and adjusted the particle count rate thresholds to prevent false triggers outside perigee.
- Accompanied by improved Flight Operations Team monitoring of SI safety, and improved ground-based SI safing procedures.

- Accompanied by improved review of mission command loads to check correct SI safing command sequences and times for perigee passages.

A universal SI safing response applies to all SI safing triggers. For autonomous safe operation, the mission timeline must be stopped. The same radiation safing thresholds are applied for all SI combinations. There is no autonomous recovery from SI safing.

Events which can trigger the science instrument safing actions:

- Observatory Safe Mode
- Normal Sun Mode transition
- Bright Star Hold
- RADMON high radiation detection
- EPHIN failure
- On-Board Computer standby timeout

Science instrument safing actions performed by SCS 107:

- Disable on-board radiation monitoring
- Terminate science mission activity
- Move Science Instrument Module (SIM) to non-instrument viewing position
- Safe ACIS detector
- Safe HRC detector
- Move SIM to HRC viewing position
- Disable SI safing process (SCS 107)

### 2.2. Mission Planning and Ground Operations

Following early mission damage to ACIS, the *Chandra* Science Operations Team[1] (SOT) and Flight Operations Team (FOT) quickly implemented a system of protecting ACIS during each perigee passage, when *Chandra* is below $\sim 75,000$ km. The science instrument protection commands used in SCS 107 are included in the mission command timeline for each perigee passage.

For solar flares and CMEs, the SOT also maintains a series of realtime proton flux and fluence monitors and predictors at the *Chandra* X-ray Center[2] (CXC). SOT members are alerted through automatic paging software and then assess past and future fluence estimates in conjunction with *Chandra*'s ground contact schedule and science mission timeline. The SOT then provides real-time direction to the FOT if instrument safing by ground command is required.

**Source data:**

- Advanced Composition Explorer[3] (ACE): Electron, Proton and Alpha Monitor (EPAM) P3 channel: 112–187 keV protons.
- Chandra Radiation Model (CRM).
- Air Force and Costello Kp geomagnetic activity index.
- GOES-8 and GOES-10 proton monitors.

**Monitors:**

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[1] `http://asc.harvard.edu/mta/sot.html`

[2] `http://asc.harvard.edu/mta/RADIATION`

[3] `http://sec.noaa.gov/ace/`

- 2 hour ACE EPAM P3 average flux.
  This monitor has an alert threshold $= 5 \times 10^4$ cts/cm$^2$-s-sr-MeV.
- *Chandra* orbital proton fluence. ACE EPAM P3 and CRM fluxes are integrated from perigee to perigee. Fluxes are attenuated by SIM and OTG transmission factors during integration.
  Monitor alert thresholds $= 1 \times 10^9, 3 \times 10^9, 9 \times 10^9 \cdots$ cts/cm$^2$-sr-MeV.
- Air Force and Costello Kp estimates. This monitor uses a seasonally variable threshold matrix for alerts.

### 2.3. Improved Radiation Modeling and Predictions

Chandra Project Science is leading a team to develop and implement an improved model for low energy proton fluxes in the *Chandra* orbit: the Chandra Radiation Model[4] (CRM).

**Design Objectives:**

- Improve science observing efficiency with low risk of RADMON triggers from trapped radiation.
- Improve real time predictions of *Chandra*'s proton fluence, for health and safety decision making.
- Refine understanding of the effect of the particle environment on ACIS for improved budgeting and control of lifetime accumulated damage.

Current *Chandra* mission planning and scheduling uses the NASA AP-8 and AE-8 radiation models. AP-8 provides poor fidelity above geostationary orbit and poor modeling of 100 keV protons. AE-8 is used for scheduling science operations. Mismatches between AE-8 predictions and observed EPHIN rates have resulted in required 10 ks "padding" on both the predicted radiation belt entry and exit times.

**Characteristics:**

- Model 100–200 keV protons, compatible with ACE EPAM P3 data.
- 9–30 $R_E$ geocentric altitude coverage.
- Indexed by Geocentric Solar Magnetospheric (GSM) coordinates and Kp.
- Flux predictions identified by region: magnetosphere, magnetosheath, solar wind, for detailed estimation of global radiation environment.
- Probabilistic flux estimates: mean, 50%, 95% fluxes.
- Multiple species and energies: p: 100–200 keV (future: p >1 MeV, He, CNO).

**Data source:** 5 year dataset (1995–2000) from the Ion Composition Subsystem (ICS) on the Energetic Particles and Ion Composition (EPIC) instrument on the Japan ISIS/NASA Geotail satelllite. Ion and electron spectrograms from the Comprehensive Plasma Instrument (CPI) Hot Plasma Analyzer provide the region identification.

**Validation:** correlation of mission fluence against aggregate ACIS damage shows CTI fluence sensitivity of $5 \times 10^{-17}$ CTI/(p/cm$^2$-sr-MeV). This is consistent with CTI increase and fluence in early mission unprotected perigees.

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[4] `http://wwwastro.msfc.nasa.gov/xray/ACIS/fluence`