*Swift/XRT* radiation damage and results from the lab using a proton-damaged CCD

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- e2v CCD-22 detector (developed for EPIC MOS camera on XMM)
- Operated in Photon Counting (PC) and Windowed Timing (WT) mode
- 4 $^{55}$Fe corner sources continuously illuminate CCD corners, used to monitor CCD performance
- Spectral resolution at launch: FWHM = 135 eV at Mn K-α (5.9 keV)
- *Swift* in Low-Earth orbit, exposed to high flux of protons (South Atlantic Anomaly)
XRT Radiation Damage

The graph shows the normalized counts per second per keV for different energies. The data is labeled as 'Cas A 2005' and 'Cas A 2010'. The graph indicates peaks and troughs corresponding to specific energies.
Trap mapping: map pixels affected by radiation damage, measure the charge losses of individual pixels

- Cas A, Tycho SNR offset pointings to cover (partially) CCD area
- Silicon line (1.85 keV) as reference energy, fit line to localize traps and measure trap depths
Trap localization

Column DETX = 256 – Tycho 2009
Recovered energy resolution
Trap depths = f(T)

- **Temperature**

  XRT CCD relies on passive cooling after TEC failure, operating between -75 and -50°C
  Dark current, shorter emission line fills traps at higher T
  Average CTI is measured to be temperature-dependent
  Temperature dependence seen in calibration corner sources analysis
Trap depths = f(E, Flux)

- **Energy dependence**
  
  Larger charge cloud will interact with more traps
  
  Averaged energy dependence measured using emission lines in Tycho, E0102, but lines too weak to measure it for each damaged pixel

- **Source flux dependence**
  
  “Sacrificial” charge effect
  
  No bright source with emission lines to test the effect on-board the XRT
Laboratory experiment

- Experimental set-up
SRC camera test facility

Space Research Centre camera test facility

Thanks to David Vernon, SRC
Proton-damaged CCD

Copy of XRT e2V CCD-22 irradiated with 10 MeV proton beam at Harwell tandem accelerator facility

Dose of $5 \times 10^8$ 10 MeV protons

Dose of $2.5 \times 10^8$ 10 MeV protons
High statistics datasets at selected energies and CCD operating temperatures:

- **ENERGY**: Oxygen (0.5 keV), Copper (0.9 keV), Aluminium (1.2 keV), Silicon (1.8 keV), Titanium (4.5 keV) and Iron (6.4 keV)

- **TEMPERATURE**: Camera cooled at set of temperatures comparable to *Swift*/XRT operational range (Ti and Si): 
  \[ \text{CCD}_T = [-100, -75, -70, -65, -60, -55, -50^\circ C] \]

- CCD uniformly illuminated, 10k frames at each setting, flux of ~ 600 single pixel X-rays/frame.
Columns with no large traps

Double radiation dose:
- Shifted in energy
- Higher noise
- Higher CTI
Laboratory results - Temperature
Laboratory results - Temperature

Titanium line, Damaged CCD – Column 132

Energy below DETY trap (keV)

-50°C
-60°C
-70°C
-100°C
Laboratory results - Temperature

\[
\text{Trap}(Y) = Y_{\text{trapped}}(Y) - Y_{\text{emitted}}(Y) + \sum_{Y_{\text{trap}}} \left[ (E_{\text{trapped}}(y) - E_{\text{emitted}}(y)) + (Y_{\text{trapped}}(y) - Y_{\text{emitted}}(y)) \right]
\]

\(E_{\text{emitted}}\) is a function of the emission time constant, depends on CCD temperature
Laboratory results - Temperature

- **A) Break**
  - Trap (411,20)

- **B) Turnover**
  - Trap (360,179)

- **C) Flatter**
  - Trap (421,354)
Lab results – Sacrificial charge

- Dataset with 3x flux
  - X-rays between trap position and measured X-ray event could fill the trap
At -75C no “step” in energy profile is seen, but gradual energy “recovery”, $t_{\text{emission}}(T=-75)<t_{\text{readout}}$

Lower temperatures (-100C) needed to see the step.
Different behaviour of trap depths on energy is an indication of different trap properties (i.e., size of defects in pixels).
Work and analysis in progress

Laboratory
- Dataset at high flux at T=-100C to investigate "sacrificial charge" effect
- Complete analysis, and introduce classification of traps based on their observed properties

Secondary neutrons
- Possible XRT damage by secondary neutrons
- Model secondary emission, if significant possibility of irradiation of CCD with neutron beam

Details of XRT trap mapping analysis in Pagani et al. 2011, A&A
Silicon FWHM

- WT observed
- PC observed
- WT corrected
- PC corrected
Backup Trap properties

**Readout time**

- XRT Windowed Timing mode observations: higher timing resolution (1.8 ms) at the expense of limited spatial information
- Use of trap info from Photon Counting mode observations does not provide the desired energy correction; also, a single scaling factor for the trap depths did not work
- Differences between modes show influence of readout times on XRT CCD traps and hints at different trap species
CTI = f(T, E, flux)

- **Choong-Ki Kim CTI equation**

\[
CTI = N_T V_v \exp \left( \frac{t_{PT}}{3 \tau_e} \right) \left[ 1 - \exp \left( -\frac{t_{PT}}{3 \tau_e} \right) \right]
\]

- **Emission time constant**

\[
\tau_e = \exp \left[ \frac{E_T}{(kT)} \right] \frac{\sigma_n v_{th} N_C}{E_T}
\]
Radiation Damage

- *Swift* in Low-Earth orbit, exposed to high flux of protons (South Atlantic Anomaly)
- Effects of displacement damage seen in the XRT CCD:
  - *hot pixels*
  - *increased dark current*
  - *charge trapping sites*
- Initial strategy to deal with decreased resolution: broadened RMFs for different epochs
- Trap energy corrections in gain files (Sept 2007-now)