Disentangling detector and background effects at soft energies in X-ray CCDs
(a work in progress)

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IACHEC 2022 Spring Workshop
The problem

- Suzaku and Chandra BI CCDs show a sharp up-turn at soft energies in flight non-X-ray background (NXB) spectra.

Comparison of NXB from Si X-ray imaging instruments
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- Athena WFI BI DEPFETs do **not** show this in Geant4 simulations.
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- eROSITA BI PNCCDs also show this.
- Athena WFI BI DEPFETs do not show this in Geant4 simulations.

1. What causes this up-turn?
   - Flickering or noisy pixels?
   - Non-Gaussian amplifier noise?
   - Improper bias subtraction?
   - Redistribution/charge loss?
   - Cosmic ray particles/secondary electrons?

2. If GCRs, why is it missing from Geant4 sims?
   - Only detector effect included is pixelization.
Soft up-turn: the XMM-Newton EPIC pn experience

From Dennerl+2004, Proc. SPIE, 5488, 61

- Dennerl+2004 identify an up-turn from:
  - Particle-induced improper offset/bias/dark correction.
  - Spatially dependent detector noise.

(Thanks to Fabio Gastaldello)
Soft up-turn: flickering or noisy pixels?

- Suzaku BI NXB spectrum from mission years 2–10
- charge injection on
  - can increase noise and flickering pixels
- default flickering pixel cleaning (cleansis)
**Soft up-turn: flickering or noisy pixels?**

- Suzaku BI and FI NXB spectra from mission years 2–10
- charge injection on
  - can increase noise and flickering pixels
- ‘noisy pixel map’ applied
  - captures all flickering pixels during mission
  - affects short exposures more
Soft up-turn: flickering or noisy pixels?

- Suzaku BI and FI NXB spectra from mission year 1
- charge injection of
- ‘noisy pixel map’ applied

- Most pristine data, reduces upturn by ~50%, but it’s still there.
Soft up-turn: non-Gaussian amplifier noise?

- If we assume it is Gaussian read-out noise with $\sigma = 2.5 \times 10^{-5}$:
  - 100 eV is $10^{-\sigma}$, or 1 every $10^{23}$ reads.
  - 1 per 33 billion years of observing.
- If we assume it is from a non-Gaussian noise tail:
  - 1 excess count per 350,000 pixel reads at 0.1–0.4 keV.
  - 3 events per XIS frame.
Soft up-turn: non-Gaussian amplifier noise?

- Suzaku BI0 (w1.8c5) ground data with flight electronics.
- 2000 bias and Fe55 frames, overclocks only.
- 1 excess sample > 27 ADU (100 eV) per 2–3 million reads.
- Explains <10% of the up-turn.
- Probably particles in the serial register.
- Analysis of in-flight data underway.
Soft up-turn: particles?

- Suzaku NXB is modulated first by orbit, less by Solar cycle.
  - $i = 31^\circ$ orbit traverses wide distribution of shielding by Earth’s magnetic field (‘cut-off rigidity’ or COR).
  - Data taken only ‘outside’ SAA.
- Up-turn is higher during times of high background (low COR).
  - Shielding affects GCR protons with $E < \text{a few GeV}$.
- Can compare to HEO/L2, but Solar activity is dominant and correlates with instrumental evolution.
Soft up-turn investigation summary

• What causes this up-turn?
  • Non-Gaussian read-out noise?
    • Probably not. Still need to account for particles in raw frame overclocks.
  • Flickering or noisy pixels?
    • Definitely some, maybe 50%. Maybe more.
  • Improper bias/dark correction?
    • To be determined.
  • Redistribution/charge loss?
    • Unlikely for BI, unless it comes from...
  • Cosmic ray particles/secondary electrons?
    • ...the interaction of CR-induced secondaries (e- and γ) in BI oxide layer. Can we simulate this?
    • Up-turn enhanced at low COR, so could be GCR-related and something missing in Geant4.

• Future steps
  • Verify energy deposit processes are being captured correctly in Geant4 post-processing.
  • Chat with eROSITA and Athena WFI experts about what they think.
  • Present to IACHEC and see what they have to say.
Soft up-turn: noisy pixels?

XIS1, CI off, NPM applied

<400 eV, COR2<6 GV

<400 eV, COR2>12 GV
The problem
MIT: soft up-turn investigation

• Why do we care about Suzaku for WFI?

1. If WFI has an up-turn similar to Suzaku, it could rival Galactic foreground at soft energies.

2. If it’s a Geant4 issue, there could be other unknown but more important issues.

3. Important to understand for future missions.
Soft upturn: redistribution/charge loss?

ACIS Calibration Report, Jan 15, 1999
ACIS FI CCD oxide-induced tail

Figure 4.8: Histogram of the CCD response to 1700 eV X-rays.

Comparison of NXB from Si X-ray imaging instruments

Maybe in the Fl
Soft upturn: redistribution/charge loss?

Figure 4.14: Fraction of single pixel events in tail as a function of characteristic absorption length in silicon.

Maybe secondary e- and X-rays generated near and interacting in the BI gate oxide.

0.4% of “modeled” counts
0.02% of total counts
Also these aren’t all X-rays and it’s a BI CCD
Soft up-turn: non-Gaussian noise?

Suzaku XIS1 ground data shows different upturn.
Soft up-turn: non-Gaussian noise?

Ground background grade ratios

Flight background grade ratios
Soft up-turn: non-Gaussian noise?

- Accumulate a statistically meaningful sample of signal-free pixel reads.
- Event corner pixels could have signal at this level.
- Ground and flight raw frames have X-rays and particles. But their overclocks don’t. (Well, not many.)
- Get ACIS ops to observe with serial clock running backwards?
- Extracted column-mean-subtracted OC regions (1024x16-ish per node per frame)
Soft upturn: non-Gaussian noise?

Suzaku and Chandra flight raw frames, over-clocks only—just read from serial register. There are particle events, however.

Suzaku XIS1 (w1.8c2) -90°C flight raw frame histograms, OC pixels only

Chandra ACIS-S3 flight data raw frame histograms, OC pixels only

~50 raw frames (0.8M samples) expect 2 non-Gaussian counts, get 0

~500 raw frames (8M samples) expect 20 non-Gaussian counts, get 80
Soft upturn: non-Gaussian noise?

Chandra ACIS-I0 flight data raw frame histograms, OC pixels only

Chandra ACIS-I1 flight data raw frame histograms, OC pixels only

255 frames

255 frames
Soft upturn: non-Gaussian noise?

Chandra ACIS-I2 flight data raw frame histograms, OC pixels only

[Graphs showing histograms with different sigma values and node numbers for 255 frames]

Chandra ACIS-I3 flight data raw frame histograms, OC pixels only

[Graphs showing histograms with different sigma values and node numbers for 530 frames]
Soft upturn: non-Gaussian noise?

Chandra ACIS-S0 flight data raw frame histograms, OC pixels only

- Node 0: $\sigma = 1.8$ ADU
- Node 1: $\sigma = 2.1$ ADU
- Node 2: $\sigma = 1.9$ ADU
- Node 3: $\sigma = 1.9$ ADU

Chandra ACIS-S1 flight data raw frame histograms, OC pixels only

- Node 0: $\sigma = 2.0$ ADU
- Node 1: $\sigma = 1.9$ ADU
- Node 2: $\sigma = 1.9$ ADU
- Node 3: $\sigma = 2.0$ ADU

255 frames

255 frames
Soft upturn: non-Gaussian noise?

Chandra ACIS-S2 flight data raw frame histograms, OC pixels only

Chandra ACIS-S3 flight data raw frame histograms, OC pixels only

255 frames

530 frames
Soft upturn: non-Gaussian noise?
Soft upturn: non-Gaussian noise?

- 3146 ACIS flight raw frames combined (gasp!) for all CCDs and readout nodes
- Overclocks only
- 1 excess sample > 27 ADU (100 eV) per 35,000 reads
- 10x the up-turn
- Probably particles in the serial register, but we should be able to account for these. (TBD)