An EPIC Tale of the Quiescent Particle Background

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Mostly K. D. Kuntz
Extended Source Analysis Software
Use Based Empirical Investigation

• Builds quiescent particle background (QPB) spectra and images for observations of extended sources that fill (or mostly fill) the FOV – i.e., annular background subtraction won’t work
• Uses a combination of Filter Wheel Closed (FWC) and corner data to capture the spectral, spatial, and temporal variation of the quiescent particle background

New Work:
• Improved understanding of the QPB (aided by adding a whole lot of data since 2008)
• Significantly improved statistics (did I mention a LOT more data?)
• Better characterization and identification of anomalous states
• Builds backgrounds for some anomalous state
• New efficient method for non-anomalous states
Review of Current (Original) Method

Where all of these quantities are spectra…
…and typical values are \( \sim 5 \times 10^{-13} \) /pixel/energy bin/s
Current Method

However, the corner data from an individual observation have very poor statistics!

So, we:

• Build a database of corner data from all observations
• Characterize the shape of each spectrum
  • The (2.5-5.0 keV)/(0.4-0.8 keV) hardness ratio sufficient
• Then for any given observation
  • Measure hardness ratio (red dot)
  • Can sum all spectra with similar spectral shape (points between green lines)
• This “augmented” corner spectrum has significantly better S/N!
Current Method

Observation

Filter-Wheel-Closed Data

Corners

FOV of interest

background = \frac{FWC \text{ FOV}}{FWC \text{ corner}} \text{ augmented corner}

Now really good stats

poor stats

Where all of these spectra are created on chip-by-chip basis
Why so Complicated?

Why not just one background spectrum?
Spectra are composed of lines and continuum
• Lines are sensitive to residual gain variation so should be fit in the observed spectrum rather than subtracted (not ESAS)
• The continuum is characterized by total count rate (R) and the (2.5-5.0 keV)/(0.4-0.8 keV) hardness ratio (H)
The QPB Varies

Filter-wheel closed (FWC) “continuum” data shows some spatial variation in count-rate and significant variation in hardness ratio (MOS1&MOS2)

Hardness ratio (H) for the MOS1, MOS2, and pn (H-meanH)
The QPB Varies

Corner data show:

• Long-term temporal variation due to solar cycle

• Temporal variation in hardness ratio
  • Anomalous states in chips 1-4, 1-5, 2-2, & 2-5
  • As of 2008, apparently also in non-anomalous chips
The QPB Varies (as of 2008)

Corner data show:

- Long-term temporal variation (due to solar cycle)
- Temporal variation in hardness ratio
- Anomalous states in chips 1-4, 1-5, 2-2, & 2-5
- Apparently also in non-anomalous chips
  - e.g., distribution of measured hardness ratio
  - was broader than expected
  - from Poisson statistics after
  - anomalous states had been
  - Removed
- Spoiler: Our understanding of this last point has changed!
Anomalous States

- Some chips show an intermittent low-energy “noise” feature
- Typically seen as:
  - higher than usual count rate
  - lower than usual hardness ratio
- States identifiable in plots of hardness ratio vs. count rate
So What’s New?

Start With:
Perennial ESAS Tasks

To keep ESAS up to date, periodically
• Update FWC data (no longer a Goddard responsibility)
• Update databases of corner spectra
• Reprocess as SAS defaults/procedures change
  • Check for significant changes in behavior
  • Update anomalous state definitions

Original methods described in Kuntz & Snowden (2008)
• Irregular updates every several years
• Finishing up(?) last(?) significant change (2017)
Perennial ESAS Tasks

Compare 2008 and with 2017 for corner data sets

<table>
<thead>
<tr>
<th>Instrument</th>
<th>2008</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOS1</td>
<td>42.2 Ms</td>
<td>303.1 Ms</td>
</tr>
<tr>
<td>MOS2</td>
<td>44.4 Ms</td>
<td>303.8 Ms</td>
</tr>
<tr>
<td>pn</td>
<td>———</td>
<td>36.2 Ms</td>
</tr>
<tr>
<td>Observations</td>
<td>~2200</td>
<td>~12230</td>
</tr>
</tbody>
</table>

- Significant increase in statistics! Due to
  - Increase in number of public observations
  - Change in construction of MOS corner data sets

In 2008 flare removal done before extracting corners. However - corner masks block soft proton flares.

Only filter out periods of high background in corners (typically entry to/exit from particle belts)
With More Statistics - Changes

- With greater number of observations
- Come greater number of extreme states observed
- Even for chips w/o anomalous states
- Had proposed ‘pseudo-anomalous’ label
- However, no clear “noise” feature
- Statistics may not be sufficient for good background
With More Statistics - Changes

- Prompted to revisit issue of distribution of hardness ratio for chips with no anomalous states
- Find that the distribution is consistent with a single mean spectrum and counting statistics for most chips
- Non-anomalous states of 1-4, 1-5, 2-2, 2-5 not so clear

A success story – non-anomalous MOS1 CCD #3
With More Statistics - Changes

• For most chips a single mean corner spectrum is sufficient
• Observations with extremely low hardness ratios may not be well modeled with a mean spectrum but
• Most (non-anomalous) observations with very low hardness ratios are short - so a problem anyway
With More Statistics - Changes

- This is a significant change from ESAS V1, only possible
  - With the greater statistics
  - Better definitions, identification and removal of anomalous states

- However the method used in ESAS V1 still applicable to observations/chips in anomalous states but…
  - Do we know enough about the anomalous states?
    - Maybe
  - Do we have sufficient statistics to implement?
    - Maybe
Comparison of hardness ratio/rate diagrams and mean spectra as a function of hardness ratio show no clear boundary between anomalous and non-anomalous states.
Anomalous States

model distribution for $H$ for Poisson stats for mean non-Anomalous spectrum

The distribution of the hardness ratio $H$ is consistent with a mean non-anomalous spectrum given Poisson statistics… but the distribution of $H$ is not consistent with a single mean anomalous spectrum
Anomalous State Questions

• At a given value of H are some observations in anomalous states while others are not?
  • Seemingly not
  • What governs the strength of the noise feature in the anomalous states?

• Do anomalous states evolve?
  • Have not seen anomalous states in chips other than the four identified in K&S 2008
  • Possible evolution for a single chip?

Change in mean H with time?
Anomalous States

- Structures in the noise features do not change significantly with hardness ratio
- Thus may be able to construct backgrounds for anomalous states where there are sufficient data.
So What About the pn?
pn Issues

• Given the longer read time of the pn, OOT events a more significant problem
  • Corner data will be strongly contaminated by the spectrum within the FOV
    • Thus corner data can be strongly contaminated by soft proton flares

• Therefore need to do flare cleaning before corner extraction
  • Flare removal a very hands-on process
  • Prospect of handling 12000 observations daunting
Flare Fitting Issues

- For region of interest, form light-curve in 2.5-8.5 keV
- Create histogram of values in light-curve
- Fit Gaussian to peak
- Remove time steps with values $>3\sigma$ from mean
- For strong flaring - fit may fail in a number of ways
Flare Fitting Issues

- Using a training set of ~2000 observations where the fits were evaluated by hand
- Built a new fitting algorithm and residual measures to allow completely automated evaluation of the goodness of fit.
- Of 10216 observations only 3773 had good flare filtering.
pn Issues

- To test goodness of flare filtering for corner data created mean corner spectrum for each FOV filter
- Here,
  - corner ≡ corner data - scaled corner data from randomized data
- If flare filtering good, expect all spectra to be the same, but that was not the result

![Graph showing spectra for different filters](image)
pn Issues

- Source of variation with filter:
  - Is it due to real problems with flare removal?
  - Is it due to problem with scaling and removing OOT?
pn Issues

• Source of problem unresolved – however
• Sort the spectra by hardness ratio and remove all that are more than $3\sigma$ different from spectra with same hardness resolves issue (slight over-simplification)
• Only 1966 observations remain
pn Issues

- Consider the distribution of the hardness ratio of the remaining corner spectra (done quadrant-by-quadrant) -
- The distributions are consistent with a mean spectrum and counting statistics

The observed distribution of hardness ratios is nearly indistinguishable from the simulated distribution.
Summary

• Newest reprocessing increases the amount of data for study of the background by >6X
• Significant changes to the way ESAS works
  • For non-anomalous MOS chips and the pn use the mean corner spectrum
  • For anomalous states use the ESAS v1 augmentation scheme of finding corner spectra with the same spectra shape as that of the observation of interest

• Still significant doubts about anomalous state spectra and non-anomalous state spectra with extreme values of the hardness ratio
• Will construct backgrounds for those chips but
• By default will produce warning and will not include in the total background spectrum
Future?

Reconsider the construction of FWC FOV/FWC corner part of the equation

\[
\text{background} = \frac{\text{FWC FOV}}{\text{FWC corner}} \text{ augmented corner}
\]

in order to find ways of increasing the S/N

Spectral model of the QPB continuum and lines for use in simultaneous fits of background and source.

And, as always, periodic updates of corner spectra databases and anomalous state definitions