Advances in the PCA energy calibration
- nearing the statistics limit

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RXTE Proportional Counter Array

- PCA is a primary instrument on board RXTE
- 5 Proportional Counter Units (PCU)
- Effective PCU area ~ 1500 cm$^2$
- 3 – 50 keV effective energy range
- Microsecond time resolution
- Main instrument for study spectral evolution and fast timing phenomena in galactic compact sources for almost 14 years. Flux and energy scale calibration
PCA Response Calibration

- Implemented as PCARMF and XPCAARF FTOOLS
- Based on the physical model (Jahoda et al. 2006, ApJS, 163, 2, 401)
  - energy-to-channel (E2C) relationship
  - quantum efficiency
  - redistribution
- 256 instrument channels
- E2C information
  - on board calibration source Am\textsubscript{241} 6 lines 13 to 60 keV
  - Cas–A iron line at ~6.4 keV (v11.1)
  - Xe L–edge in Crab spectra (v11.7)
- Flux calibration
  - Crab
    - Power law spectral distribution is assumed
    - $\Gamma=2.11$, Norm (1 kev) = 11.0, $N_H = 0.34 \times 10^{22}$ cm$^{-2}$
- Current version v11.7 presents a major change in minimization method
Overall we need 43 parameters to describe response for a particular detector layer.
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PCA Calibration Data

BNL ground calibration data on resolution: $\Delta E=1 \text{ keV} @ 6\text{keV} \& 2 \text{keV} @ 22\text{keV}$

Crab
- Flux calibration
- Quantum efficiency parameters

Am 241
- E2C calibration
- 6 Lines from 13 to 60 keV
- Resolution coeff. (v11.7)

Cas A
- Fe K\(\alpha\) Line at $\sim 6.6$ keV
- Calibration source for v11.1 and earlier
- Test Source for v11.7
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PCA Calibration Data Flow (PCARMF v11.1 and earlier)

- Am$_{241}$ + Cas A spectra fitted in channel space
- Minimization of E2C parameters
- Crab fits to get quantum efficiency parameters for different dates
- Averaging and fitting trends

Implemented as combination of FORTRAN and UNIX shell scripts
PCA Response Minimization Method

1. Import PCARMF code into XSPEC as a local model.
2. XSPEC session generator (tcl script).
3. CRAB + Am$_{241}$ data throughout RXTE mission are fit with pcarmf model parameters in one XSPEC session.
**XSPEC session for PCARMF model fit**

<table>
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<tr>
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</tr>
<tr>
<td>a</td>
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<tr>
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<tr>
<td>Date</td>
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<td>501..</td>
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</tr>
</tbody>
</table>

**Crab**

**Layer**

**PCU**

**PCA**

**Epoch 3**

**Epoch 4**
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**XSPEC session for PCARMF model fit**

- 18 Crab observations
- 13 Am\textsubscript{241} observations
- Data sets \((18+13) \times 3 = 93\)
- Model parameters \((48 \times 18 + 52 \times 13) \times 3 = 4620\)
- 74 free parameters
PCARMF model fit results

- Fit strongly suggested different resolution coefficients $\Delta ch = B \sqrt{(aE + b)}$
  - $v11.1 \ a = 0.121 \ b = 0.422$
  - $v11.7 \ a = 0.17 \ b = 0.0 \Rightarrow \Delta ch = B \sqrt{aE}$
  - Consistent with Brookhaven data
  - Requires broader redistribution function for high energies and narrower for low energies

- Putting quadratic time dependence $e2c$ coefficients to zero greatly improved the fit and simplified $e2c$ model $ch = A + B \times E + C \times E^2$
  - $v11.1 : A = A_0 + A_1 \Delta T + A_2 (\Delta T)^2$
  - $v11.7 \ A_2 = 0.0 \Rightarrow A = A_0 + A_1 \Delta T$
  - Same story for $B$
  - Makes sense physically

- New $e2c$ model renders 5th epoch for $e2c$ relationship obsolete
  - Epoch 5 remains for PCU 0 and PCU 1 due to loss of propane channel with the epoch start data at the event of propane loss
PCARMF v11.1 vs v11.7: Crab Test

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Energy-to-Channel Scale Test

Am$_{241}$ v11.7

Cas A – Fe K$_\alpha$ Line

Am$_{241}$ v11.1

Crab – Xe L edge
Systematic Error

- PCU 2
- Crab data only
- Best fit parameters

\[ \chi^2_{\text{red}} = 3.2 \]
\[ \chi^2_{\text{red}} = 2.1 \]
\[ \chi^2_{\text{red}} = 1.2 \]

- Systematic error is 0.5–0.8%
- Very high statistic data – 1%, but not more 1.5%
- v11.1 response 1–2% sys. error

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### PCARMF v11.1 vs v11.7

<table>
<thead>
<tr>
<th></th>
<th>PCARMF v11.1</th>
<th>PCARMF v11.7</th>
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</thead>
<tbody>
<tr>
<td><strong>e2c relationship</strong></td>
<td>• 5 epochs</td>
<td>• 4 epoch (except PCU 0,1)</td>
</tr>
<tr>
<td></td>
<td>• 7 coefficients per epoch</td>
<td>• 5 coeff./epoch</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>• $\Delta ch = B \sqrt{(aE + b)}$</td>
<td>• $\Delta ch = B \sqrt{(aE)}$</td>
</tr>
<tr>
<td></td>
<td>• $a = 0.121, \ b = 0.422$</td>
<td>• $a = \sim 0.17$</td>
</tr>
<tr>
<td><strong>Quantum efficiency</strong></td>
<td></td>
<td><strong>Escape lines have different normalizations</strong></td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>• Show trends both in index and norm in Crab</td>
<td>• Index and normalization is stable with only minor trends</td>
</tr>
<tr>
<td></td>
<td>• gradually worsening $\chi^2$</td>
<td>• No signs of decline in $\chi^2$ quality</td>
</tr>
<tr>
<td></td>
<td>• PCUs 0 &amp; 1 are unusable after propane loss</td>
<td>• e2c is stable and predictable</td>
</tr>
<tr>
<td></td>
<td>• e2c is not reliable esp. for</td>
<td></td>
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*5th IACHEC Meeting, MBL, April 12*
SUMMARY

Conclusion

- New response is a huge step up in RXTE/PCA calibration quality and instrument understanding
- PCA is healthy, performing well and can operate several more

Future Plans

- To test theoretical Crab models (as per Weisskopf et al 2010)
- To work towards more universal calibration with other mission (Kirsch et al. 2005, XMM-Newton)
- Apply response minimization method for new instruments (ASTROSAT?)