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Updates to the RMF model in the ACIS FI CCDs

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Abstract

This memo describes two updates to the RMF model in the ACIS FI chips:

1. additional exponential tail in the pre-CTI response
2. new model to the CTI scatter matrix obtained without `add_cti.pro`

1 Ideal response

ECS lines have low-energy spectral shoulders not adequately described by the MIT ACIS model (Fig. 1). These shoulders are adequately fit (Fig. 2) with the modified exponential tail law,

$$f(E) = A \times \exp\left(-\frac{(E_0 - E)^\alpha}{\tau^\alpha}\right) \quad \text{for } E < E_0, \qquad f(E) = 0 \quad \text{for } E > E_0, \tag{1}$$

where E_0 equals to the line energy. Figure 3 shows that in all CCDs, the exponential tails adequately describe the data when the parameters are tied as follows

$$\begin{aligned} \alpha &= 2 \\ \tau &= 0.2334 \times E_{\text{keV}}^{0.7} \\ \text{flux} &= (\text{Line Flux}) \times E_{\text{keV}}^{-0.5} \times 0.056 \end{aligned} \tag{2}$$

At high energies, the absolute width of the tail increases but the relative flux becomes small, $< 2.5\%$ for $E > 5$ keV. At low energies, the relative flux increases, $f \sim 7\%$ for $E = 0.6 - 0.7$ keV, but the width of the tail because smaller.

DO WE EXPECT THAT THE TAIL DISAPPERARS BELOW SOME ENERGY?

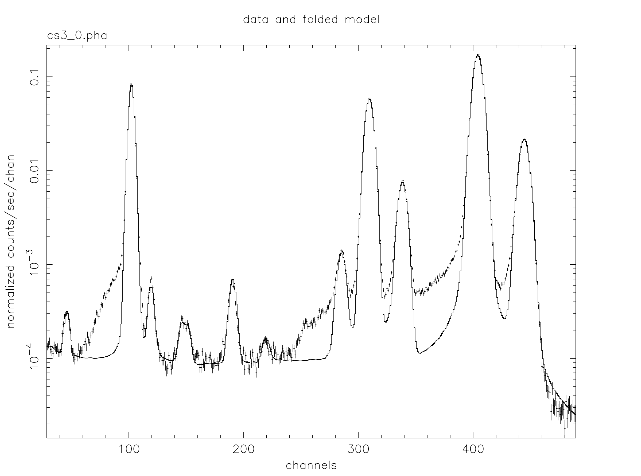

Fig. 1: Example of the ECS spectrum near the readout (CHIPY < 64 in I3). All lines have low-energy shoulders which are absent in the RMF model.

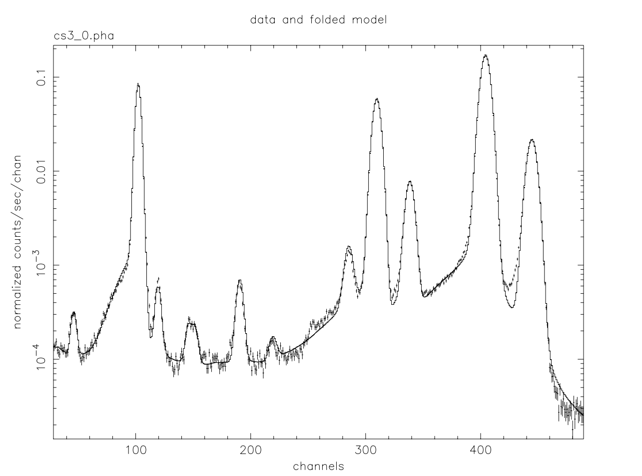

Fig. 2: The same as Fig. 1 but with exponential tails (eq. 1) added to the RMF model.

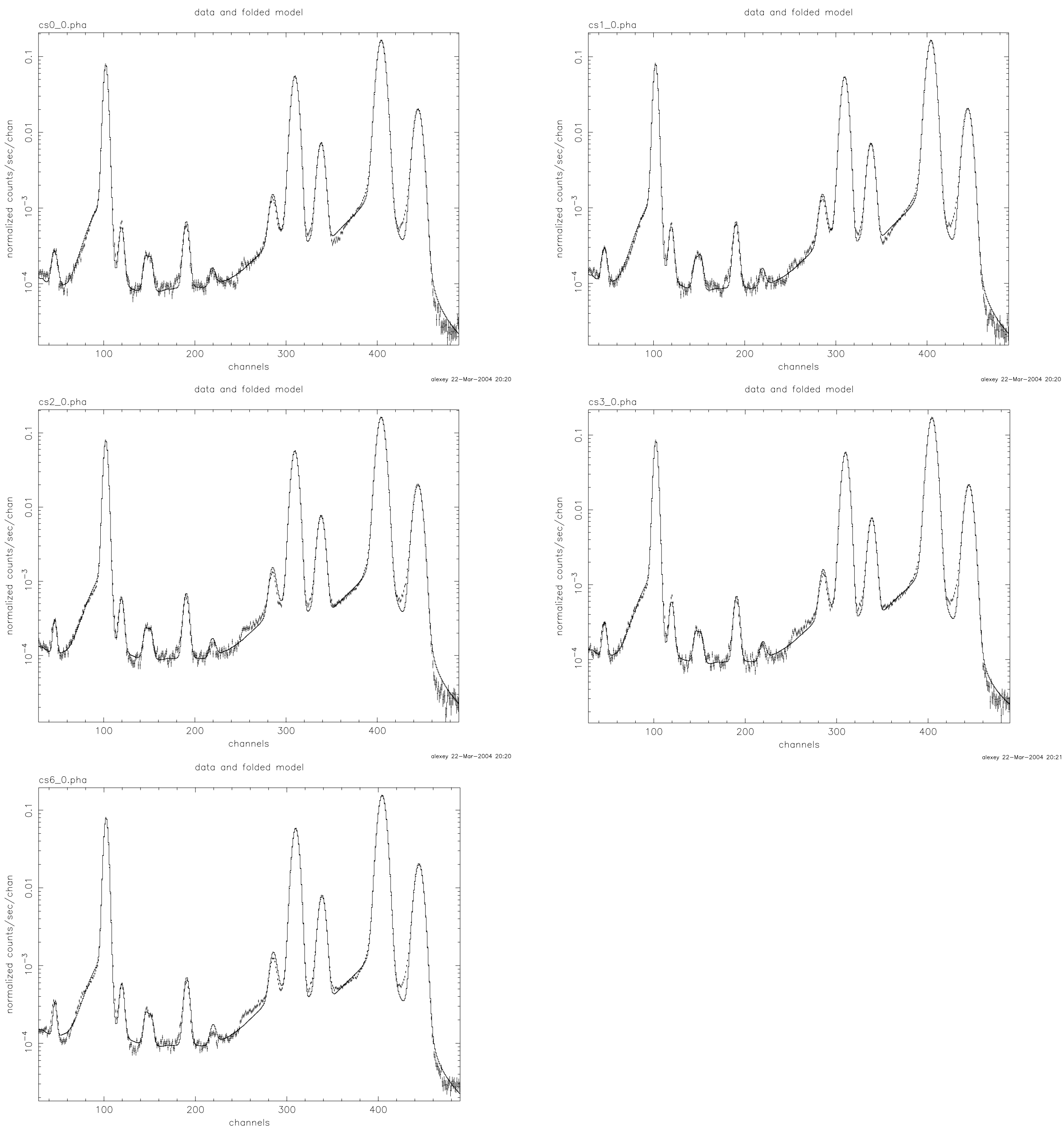

Fig. 3: Fits of the ECS data at `CHIPY` < 64 in I0, I1, I2, I3, and S2 with the exponential tail added to the model.

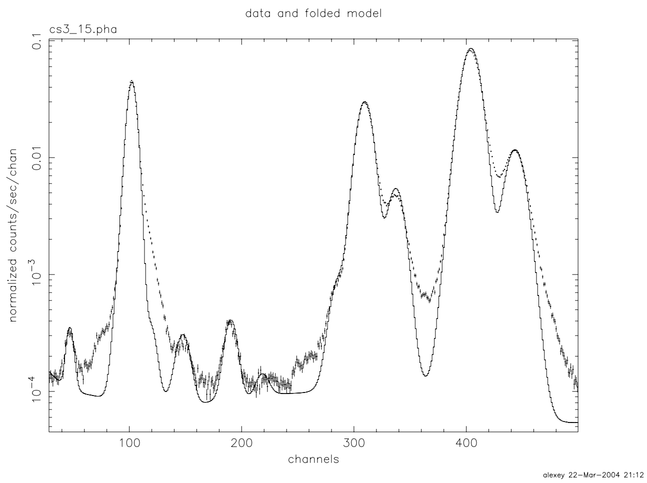

Fig. 4: Example of the ECS spectrum in the top region of the chip (CHIPY > 960 in I3). The CTI scatter model is obtained from the add_cti.pro simulations.

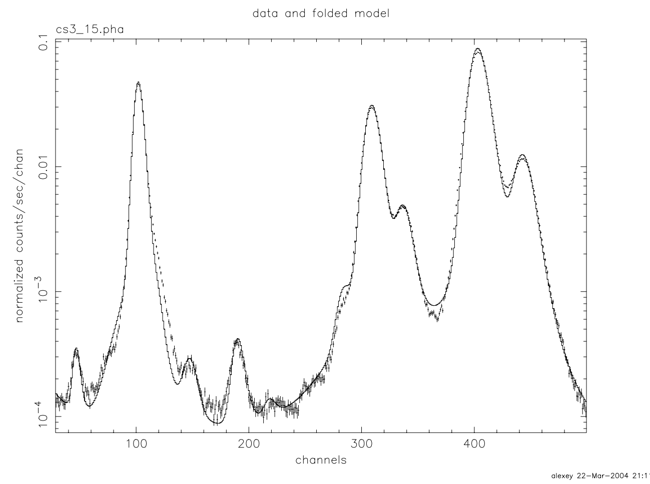

Fig. 5: The same as Fig. 4 but the CTI scatter matrix is via eq. 3–4.

2 Scatter matrix

Problem: add_cti.pro does not adequately describe the wings in the CTI-induced response scatter (Fig. 4).

Proposed modification: The scatter matrix is described by the modified asymmetric Lorentz function:

$$R(E) = \begin{cases} (1 + (E - E_0)^2/\Delta^2)^{-\alpha_1} & \text{for } E < E_0 \\ (1 + (E - E_0)^2/\Delta^2)^{-\alpha_2} & \text{for } E > E_0 \end{cases} \tag{3}$$

The quantity 2Δ is somewhat equivalent to the FWHM of the line. The FI data are adequately described if the coefficients are tied as follows

$$\alpha_1 = 3.70, \quad \alpha_2 = 1.90, \quad \text{and} \quad \Delta = \Delta(E) \tag{4}$$

(see Fig. 5). Note that the average energy for the modified Lorenz function ($\langle E \rangle = \int E R(E)\, dE / \int R(E)\, dE$) is

$$\langle E \rangle = E_0 + 0.2779\Delta \tag{5}$$

2.1 Energy dependence of the CTI-induced line width

The high-energy ECS lines (Al-K, Ti-K, and Mn-K) can be well-fit simultaneously if Δ in eq. (3) is proportional to $E^{0.55}$. However, the extrapolation of this dependence to low energies is uncertain and we don't have good calibration data to verify it. Alternatively, we can use the energy dependence of the line width provided by add_cti.pro and simply normalize it using the observed ECS spectra. The following simple function provides a good fit to the add_cti.pro results:

$$\Delta \propto (E_0^{0.12} + 0.3E_0) \tag{6}$$

where E_0 is in keV (Fig. 6). In the ECS energy range, $E = 1.5 - 6.0$ keV, it is indeed close to the $E^{0.55}$ law (dotted line in Fig. 6).

2.2 Derivation of the scatter matrix

Extract 256×32 spectra in each CCD. Fit them with a 5-line model using the pre-CTI RMF. Each line is represented by eq. (3), where the slopes are fixed at the values in eq. (4) and the widths are tied according to eq. (6),

$$\Delta_{\text{Al-K}} : \Delta_{\text{Ti-Ka}} : \Delta_{\text{Ti-Kb}} : \Delta_{\text{Mn-Ka}} : \Delta_{\text{Mn-Kb}} = 1 : 1.7066 : 1.7995 : 2.0312 : 2.1397 \tag{7}$$

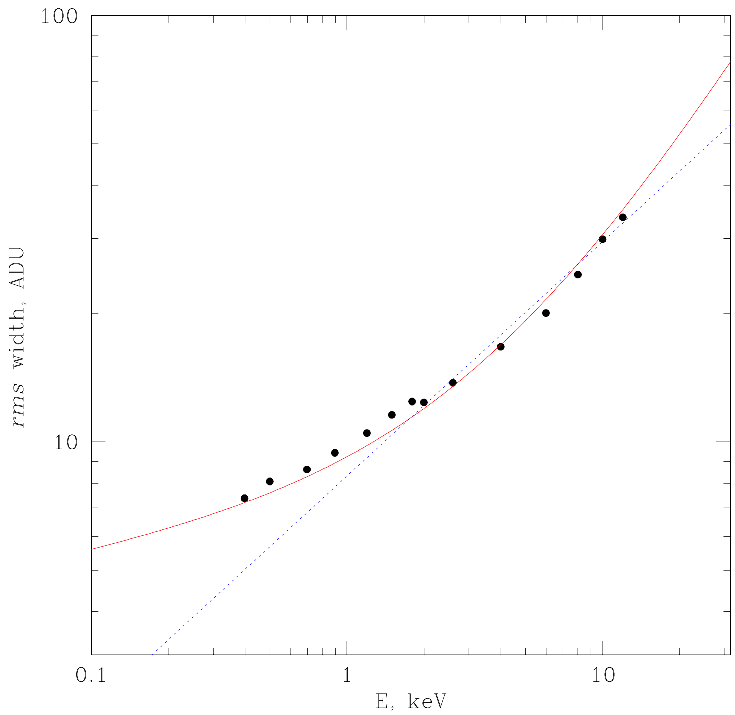

Fig. 6: A representative dependence of line width on energy derived from `add_cti.pro` (node 3 of I3, CHIPY $= 900$). The red line represents eq. (6), and the dotted blue line corresponds to $\Delta \propto E^{0.55}$.

The fit gives the measured width for Al-Ka at each location. These measurements are smoothed by a polynomial fit to the $\Delta(\texttt{CHIPY})$ dependence within each node. The scatter matrix is using eq. 4 with a shift to compensate the average offset in energy given by eq. 5.

2.3 Scatter matrix tweak

1. Fit the 256×32 spectra with the zero-order RMFs.
2. Fit deviations to the CTI + gain model and update the locations in the CTI scatter matrix.
3. Test on ECS and on E0102. Make the global low-E tweak if needed.

   I keep the tweak from original FI RMFs (see AV's notes for `calcrmf2`):

$$G = 1 - \frac{0.008}{1 + |E - 0.95|^3/0.253^3} \quad (8)$$

4. Test again using the ECS and E0102 data:

E, keV	Source	Gain correction		
		Average	Scatter	Maximum
0.64	E0102, O-lines	-0.2%	$\pm 0.7\%$	
0.95	E0102, Ne-lines	$+0.0\%$	$\pm 0.4\%$	
1.487	ECS, Al-Ka	-0.07%	$\pm 0.2\%$	$\pm 0.55\%$
4.510	ECS, Ti-Ka	$+0.08\%$	$\pm 0.08\%$	-0.16%, $+0.27\%$
5.898	ECS, Mn-Ka	-0.03%	$\pm 0.03\%$	-0.28%, $+0.14\%$

Near the ACIS-I aimpoint (I3, node3, CHIPY $= 1000$, gain corrections are $+0.15\%$, $+0.02\%$, and -0.06% for the Al-, Ti-, and Mn-Ka lines, respectively.

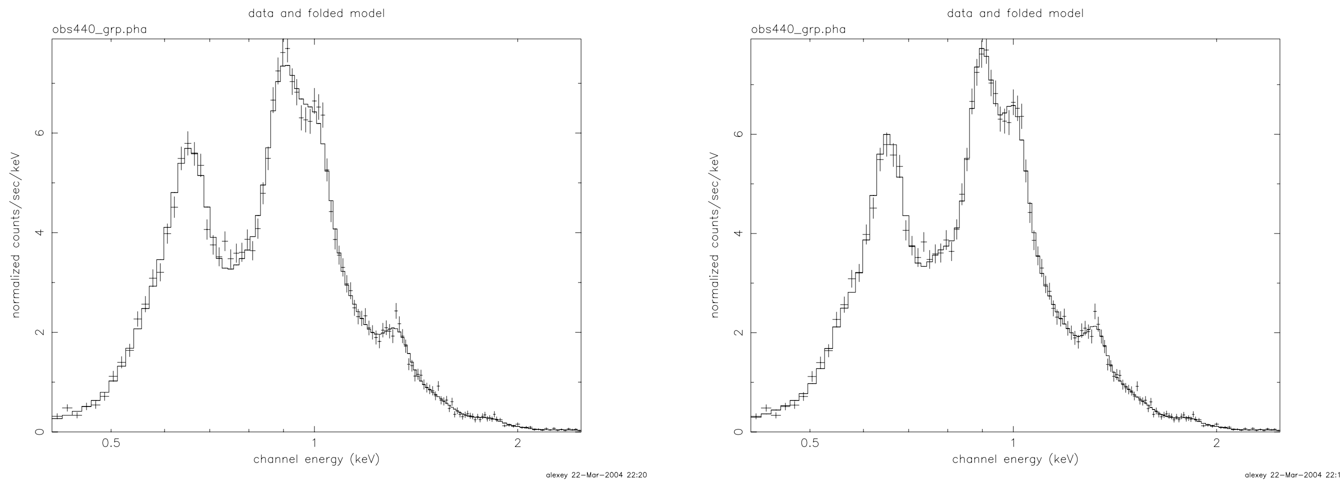

Fig. 7: Fit to the E0102 spectrum (OBSID440, I3,X=655,Y=912) using the old and new RMFs (left and right, respectively). Notice more accurate line widths when using the new RMF.

5. Compute matching gain table.
6. Test for uniformity on Mn/Fe-L.

   EpochI: gain uniform within $\pm 0.5\%$ *rms* (consistent with statistical scatter); maximum deviations: -1.4%, $+1.0\%$.

   EpochX: uniformity $\pm 0.8\%$ *rms* (consistent with statistical scatter); same average as in EpochI

3 Astrophysical tests

The improvements of the ECS fits due to new RMF model are illustrated by Figs. 1–2 and 4–5. I did several extra tests using the astrophysical sources.

3.1 E0102

An observation of E0102 near the readout in ACIS-I is shown in Fig. 7 along with the best fit to the grating-fixed line ratios model (**REF?**). The new RMF gives the line widths more consistent with the data and thus improves the χ^2 from 124.1 to 96.7 per 100 dof.

3.2 A1060

To illustrate the effect of the RMF updates on the continuum fits, I've used an ACIS-I observation of the galaxy cluster A1060. The spectrum was fit using the MEKAL+Galactic absorption model. The χ^2 is improved somewhat and the spectral parameters are almost unaffected:

$$T: \quad 3.653 \to 3.619$$
$$K: \quad 4.004 \to 4.009$$
$$\chi^2: \quad 157.9 \to 145.2$$