A measurement of the CTI effect on the quantum efficiency of the FI chips

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The quantum efficiency of the ACIS FI CCDs decreases at high energies and far from the read-out as a result of the CTI. This effect is readily visible in the temperature maps of hot clusters (e.g. Coma). Here we investigate the energy- and `CHIPY`-dependence of this effect using calibration observations of the Coma cluster and SNR G21.5–0.9 at the focal plane temperature -110C.

At 6 keV, the results derived here are in agreement with the lab measurement by C. Grant in both the amplitude of the effect and its `CHIPY` dependence.

1 Related studies

There are two independent studies of the CTI effect on the CCD QE using the calibration source and both lab models (Catherine Grant at MIT) and in-flight data (Leisa Townsley at PSU).

Both these studies consistently indicate a decrease of the QE at the energy of the Mn Ka line (6 kev) but not at the lower-energy lines (0.5–1.5 keV). Also, the QE at 5.9 keV seems to reach a "saturation" value of ≈ 0.8 at large `CHIPY` compared to `CHIPY`=0 (i.e., near the readout).

Unfortunately, these results cannot be directly used for the calibration of the position-dependent CCD QE because the QE is measured essentially at only one energy. The energy dependence of the CTI effect on the QE can be established using observations of the same X-ray source in different regions of the CCD.

2 Data

2.1 G21.5–0.9

The SNR G21.5–0.9 was observed in Nov-Dec of 1999 in I0, I1, I2, I3, and S2 chips (Fig. 2.1). The average source `CHIPY` for each observation is presented in Table 1. Assuming that the HRMA energy-dependent vignetting is well-

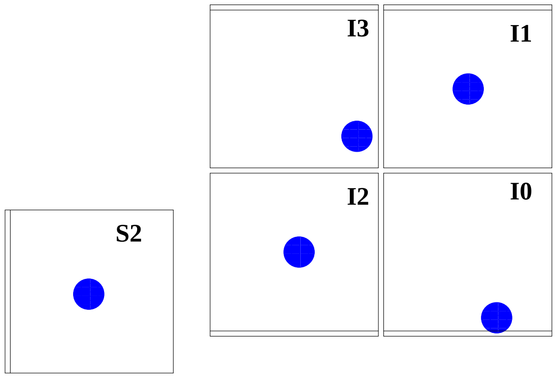

Figure 1: Observations of G21.5–0.9. Circles mark locations of the SNR. Double line indicates the CCD read-out

Table 1: Average `CHIPY` of G21.5–0.9

obsid	CCD	`CHIPY`
1441	i0	197
1442	i1	593
1443	i2	500
1434	i3	840
1233	s2	512

calibrated we can use the I0 pointing as a reference and determine the QE in the middle of I1, I2, and S2, and at large `CHIPY`'s for I3.

The angular diameter of the SNR is 1 arcmin, which is much smaller than the angular scale at which the CTI effect is expected to vary.

2.2 Coma cluster

Coma was observed in Nov-Dec of 1999 in a series of pointings in which the source position was fixed with respect to the HRMA and ACIS was moved along the Z-axis by approximately 3 arcmin. With this setup, the same region of the Coma cluster was observed in two pointings in S2 at the same off-axis angle, but at different `CHIPY`'s. This opens a possibility to derive the relative QE without assuming that the vignetting is perfectly known. Unfortunately, Z motions are parallel to the `CHIPX` direction in the ACIS-I CCDs, and therefore the QE measurement cannot be performed with them.

We defined three rectangular regions which are within the S2 field of view in both pointings (Fig. 2 and Table 2). Using region #1, we can derive the relative change in the CCD QE between `CHIPY`=175 and 464, with r2 — from 390 to

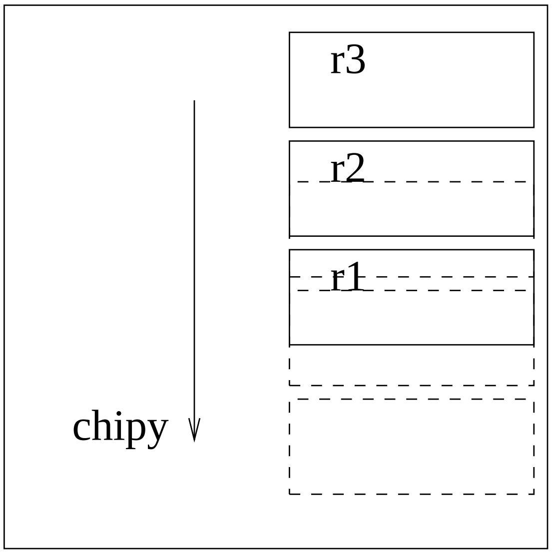

Figure 2: S2 observations of the Coma cluster. Solid lines show the positions of regions r1,r2,r3 in obsid 556, and dashed lines — in obsid 1086. Readout is at the r3 side.

681, and with r3 — from 600 to 890. Combining the data for all regions, we can derive the QE change essentially across the entire `CHIPY`>400 region.

3 Data reduction

Since we want to compare the observed spectra of G21.5–0.9 and the Coma cluster in different chip positions, we first need to correct for the CTI-caused gain variations across the CCDs. I used `acis_process_events` with the `acisD1999-09-16gainN0003.fits` gain table to recompute photon energies and PI channels.

I then extracted the source spectra in PI channels in the *same* regions in

Table 2: S2 observations of the Coma cluster

Region	Average `CHIPY`	
	obsid 1086	obsid 556
r1	892	605
r2	681	390
r3	464	175

sky coordinates. The background spectra were produced from the blank sky data provided by M. Markevitch. RMFs were generated from the –110C FEFs (the FEFs were modified to correct the problem with negative Gaussian components), and ARFs were calculated using the latest HRMA area calibration files and the spatially uniform CCD QE files distributed with CIAO. The QE curves are individually calibrated for each CCD and presumably are accurate at the readout.

For perfectly calibrated CCD QE, HRMA vignetting, and RMFs, these spectra should produce identical fits in XSPEC.

3.1 Results for G21.5–0.9

I have chosen the I0 observation as a reference because it is the closest to the readout. The source spectrum was well-fit with the broken power law plus absorption model (Fig 3) with $N_H = 2.453 \times 10^{22}$, the lower energy photon index $\Gamma_1 = 1.863$, the higher-energy photon index $\Gamma_2 = 0.4$, and the break energy $E = 7.78\,\mathrm{keV}$. The deviations of the data from the model are no more than 10% at $E > 2\,\mathrm{keV}$. I then used the same model (including normalization) for I1,I2,I3, and S2.

The result for the I3 pointing in shown in Fig. 4 and the ratio is shown separately in Fig. 5. There is a clear deficit of the data relative to the model at $E > 2.5 - 3\,\mathrm{keV}$. The data around 1.5 keV may indicate some residual gain variations of order 1–2%, but they cannot explain the effect at high energies.

Note that the analytic model in Fig. 3 and 4 was convolved with the RMFs generated for the appropriate CCD regions; therefore, the effect of the varying energy resolution was corrected at least in the first order.

The I1, I2, and S2 spectra of G21.5–0.9 (all taken in the middle of the chip) show the same effect as that in Fig 4–5 — the ratio between the observed spectrum and the model assuming uniform QE decreases approximately linearly with $\log E$ from ≈ 1 at $E = 2.5\,\mathrm{keV}$ to ≈ 0.8 at $E = 6\,\mathrm{keV}$, and the trend seems to continue to higher energies reaching ≈ 0.7 at 8–9 keV.

If this is interpreted as the QE decrease due to CTI we conclude that

1. The energy dependence of the QE can be approximated by a linear function of $\log E$ at $E > 2.5\,\mathrm{keV}$,
2. There is no noticeable change in the QE between `CHIPY`$\approx$500 and 900
3. The effect at $E = 6$ keV is 20%.

The last two points perfectly agree with what is found in the lab model at –110C (see Catherine Grant's web page).

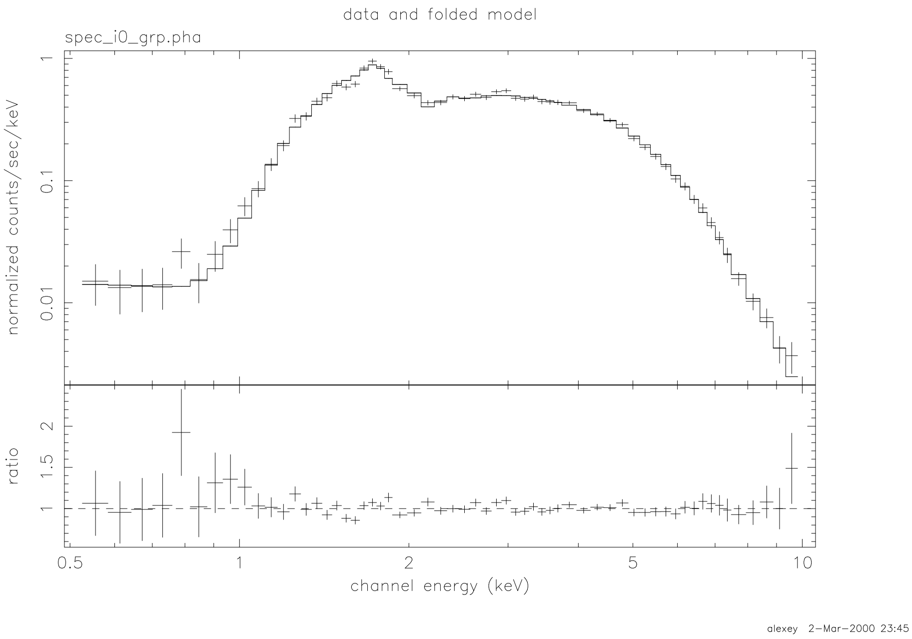

Figure 3: G21.5–0.9 spectrum in I0 (`CHIPY`=197).

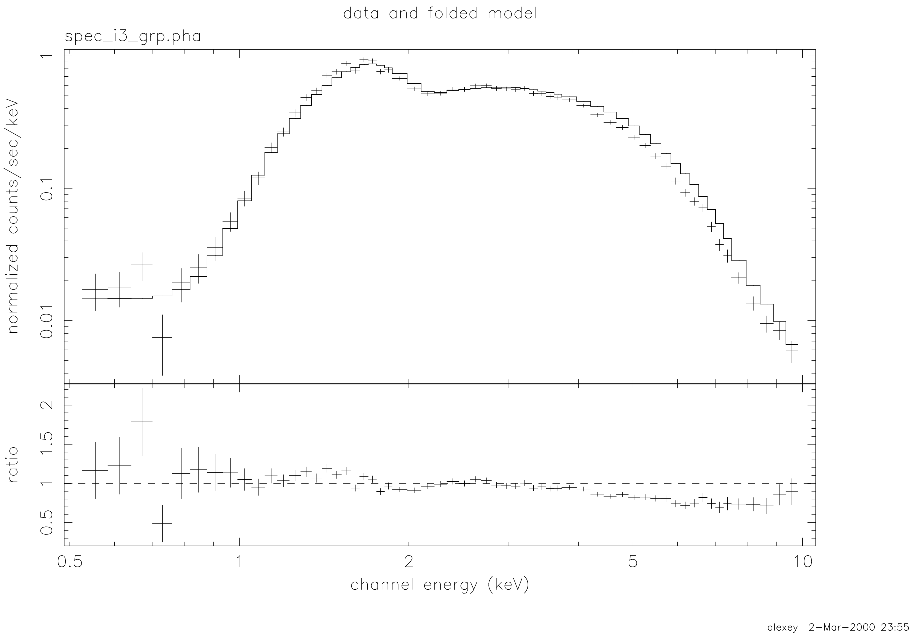

Figure 4: G21.5–0.9 spectrum in I3 (`CHIPY`=840). The model was taken from the I0 fit (Fig. 3)

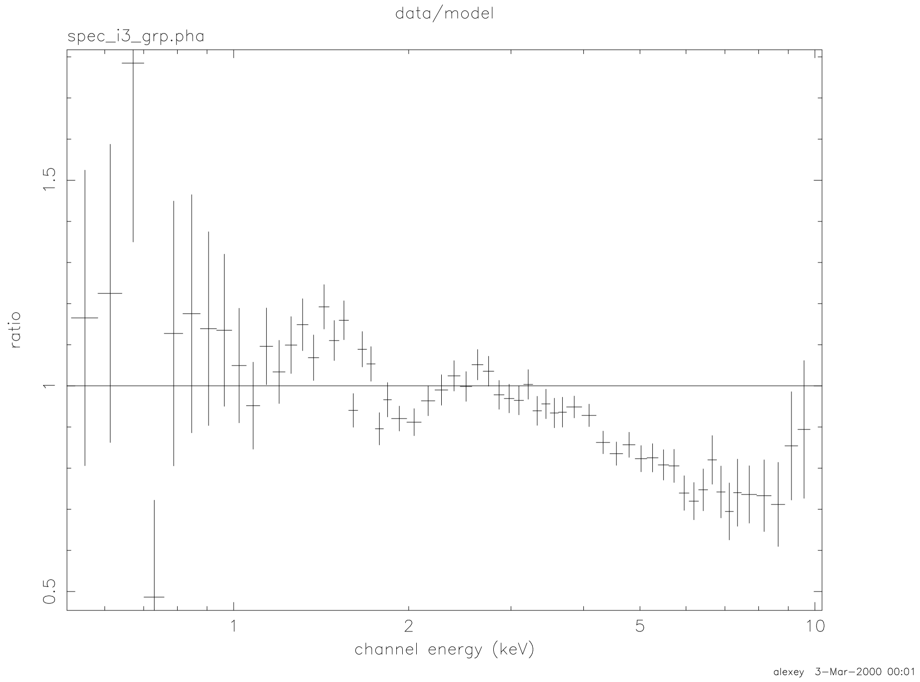

Figure 5: The ratio panel from Fig. 4

3.2 Results for the Coma cluster

For the Coma cluster, I fit the obsid# 556 data with the Raymond-Smith plus absorption model and then apply the same model to the obsid#1086 data which is at the same off-axis angle but at higher `CHIPY`. In this case, the "reference" spectra in obsid 556 are already affected by the QE decrease and we are measuring the relative change of the QE between the respective chipy positions.

For the region 3 (`CHIPY` change 175 to 464), the effect is very similar to that in G21.5–0.9 (Fig. 6). The region 2 data indicate, albeit marginally, the 10% change of QE at $E = 6\,\mathrm{keV}$ between `CHIPY`=390 and 690 (Fig 7). Finally, the region 1 data indicate that there is no detectable change in the QE between `CHIPY`=605 and 890.

Thus, the Coma cluster results fully support the conclusions conclusion from the G21.5–0.9 data (page 8).

4 Comparison with MIT and PSU results

Here we assume that the effects seen in the G21.5–0.9 and Coma data are entirely due to the CTI-induced decrease in the CCD QE. Figure 9 shows the `CHIPY` dependence of the QE at $E = 6$ keV derived from the lab measurements

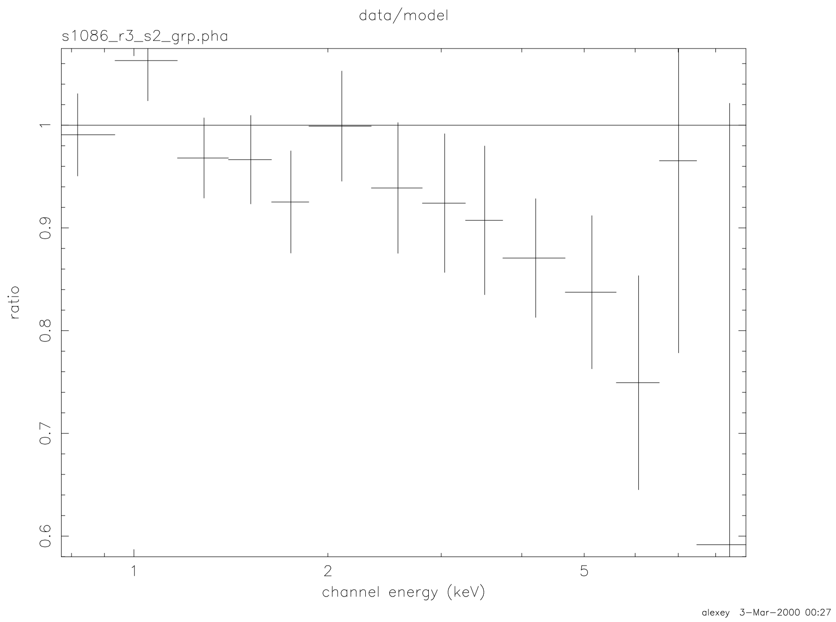

Figure 6: Coma cluster: the ratio between the R3 data at CHIPY=464 and model at CHIPY=175

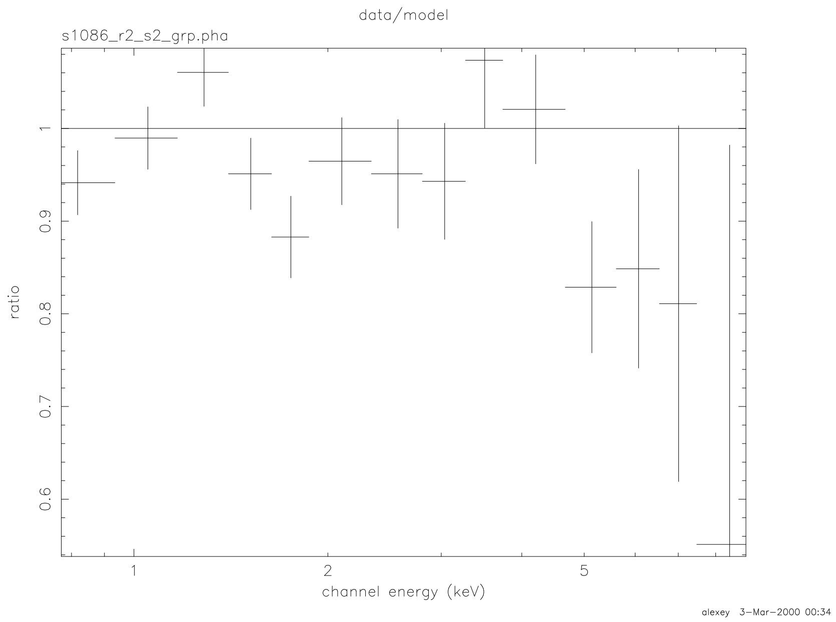

Figure 7: Coma cluster: the ratio between the R2 data at CHIPY=687 and model at CHIPY=390

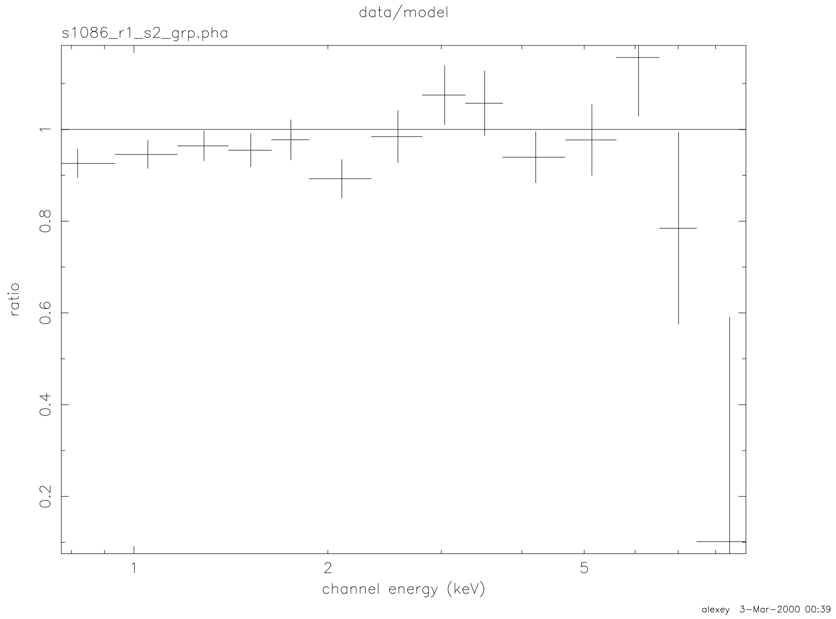

Figure 8: Coma cluster: the ratio between the R1 data at CHIPY=892 and model at CHIPY=605

in MIT, PSU in-flight calibration source data averaged over all I3 nodes, and the in-flight astronomical source data described here.

The conclusions can be summarized as follows:

1. The energy dependence of the QE decrease can be approximated by a linear function, $\Delta\mathrm{QE} = A + B \times \log E$ at $E > 2.5\,\mathrm{keV}$,

2. The CHIPY dependence and the amplitude of the effect is in agreement with the MIT lab measurements.

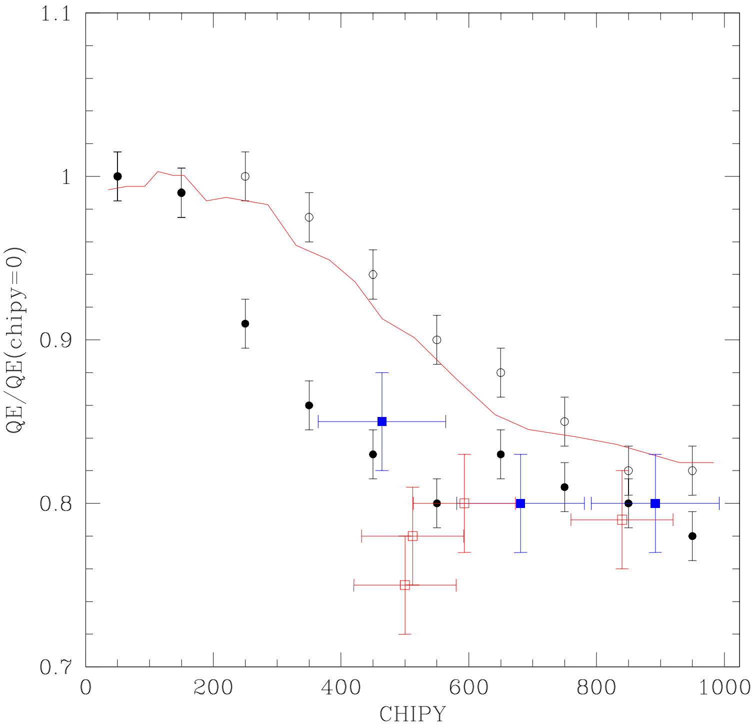

Figure 9: The `CHIPY` dependence of the QE at $E = 6\,\mathrm{keV}$. Circles show the MIT lab model measurements at –110C (filled circles) and –120C (open circles). The solid line shows the PSU in-flight measurements at –110C (??, their Fig. 7). Blue filled squares show the results derived from the Coma data, and red open squares — from the G21.5–0.9 data.