Non-uniformity of CTI

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Abstract

It is found that CTI is significantly non-uniform over a chip. Thus the energy resolution of SIS is degrading due to both the RDD effect and the non-uniformity of CTI. The former is significant only in 4 ccd mode, but the latter is expected to contribute to all 1/2/4 mode data. The energy resolution in 1 ccd mode was ∼130 eV (@6.4 keV) just after the launch and is now (2.5 years after the launch) ∼220–250 eV, which is due to the non-uniformity of CTI. In the case of SIS, it is practically impossible to correct such non-uniform CTI for the data, and this effect should be included in the response matrices.

1 Cas A line profile

Cas A is observed every year for the purpose of SIS calibration. Three sets of data are available now; they are those obtained in August 1993, July 1994 and August 1995. Cas A data were taken in various modes with various pointing positions, but 1 ccd faint mode data were taken every year from the standard chips at exactly the same pointing position as reference. We show in figure 1 the energy spectra calculated from such reference data. Standard data selection criterion was applied and the data were corrected for DFE, echo and CTI. The CTI values used are those determined from Cas A data in 1994 (ASCA news letter No.3; ISAS research note 574). Note that RDD effect is still negligible for 1 ccd data. Thus the spectra should have the best quality currently available.

As seen from figure 1, degradation of the energy resolution is clear. Because the RDD effect is negligible for these data, we suspect that non-uniformity of CTI causes such degradation of energy resolution. In the following chapters, we investigate the uniformity of the CTI.

2 CTI measurements with Cas A data in 1995

During the Cas A observations in 1994, we could obtain only 3 pointings for each chip because of the limited observation time. Three pointings are minimum to calculate both parallel and serial CTI, and hence we could not check the uniformity of CTI. However, in 1995 observations, we obtained 4 pointings for standard chips. Thus we can check the uniformity of CTI for the standard chips.

We show in figure 2 schematically the pointing positions of the standard chips in 1995 Cas A observations. Using these data we can determine parallel CTI at two different positions. One is between **o** and **h** and the other is between **v** and **x**. We first calculated gain difference between

pointing positions using Si, S, Fe lines. We assumed that CTI is constant against photon energy, *i.e.* charge lost by CTI is proportional to the original charge packet size. This was good approximation for most of the data, although some data showed complex energy dependence. The gain differences are listed in table 1. CTI were calculated from the gain differences. For example, C_{P1} is calculated

Table 1: Gain difference between pointing positions (Cas A 1995)

Sensor	**x–h**	**x–v**	**h–o**
S0	2.06±0.11 %	1.54±0.11 %	0.53±0.10 %
S1	0.72±0.12 %	1.61±0.11 %	0.90±0.11 %

Errors are in 90 % confidence limit.

from the gain difference between **v** and **x**, and C_{P2} from the gain difference between **o** and **h**. The results are listed in table 2. Expected CTIs, which are extrapolated from the CTI determined by Cas A data in 1994, are also listed in the table. As seen from table 2, difference of parallel

Table 2: CTI of the standard chips in August 1995

	Parallel CTI ($\times 10^{-5}$/tr)			Serial CTI ($\times 10^{-5}$/tr)	
Chip	C_{P1}	C_{P2}	Extrapolation[a]	C_S	Extrapolation[a]
S0C1	6.2±0.5	2.2±0.4	4.0	11.4±0.5	5.3
S1C3	6.5±0.5	3.6±0.4	4.1	4.9±0.1	–0.4

Errors are in 90 % confidence limit.

[a]Extrapolated CTI from the value in July 1994.

CTIs with position (C_{P1} and C_{P2}) is very large. Serial CTIs are also very different from the extrapolated values based on 1994 measurements. This is because serial CTI in 1994 measurement was determined under the assumption of uniform parallel and ST CTI (CTI associated with the charge transfer from imaging area to frame store area), which is not the case. Even for the serial CTI determined from 1995 observations, uniformity of ST CTI is still assumed. If ST CTI is not uniform over the chip, which is very plausible, serial CTI may be different from the value listed in the table. Because the number of transfer associated with ST CTI is constant (422) for all the pixels in a chip, there is no way to directly measure ST CTI. According to the investigation above, it is suspected that non-uniformity of CTI is very large and may be comparable to the mean CTI.

3 Column to column variations of parallel CTI

Cas A observation at position **o** of the standard chips has relatively long exposure to obtain enough statistics for iron line. This means that more than enough photons are available for Si line. We found that we can make moderate statistics of energy spectra even if we select events from a single column which lies under the brightest part of Cas A. Thus we can compare column to column variations of the energy spectra.

We show in figure 3 an example of energy spectra calculated from single column data of S1C3 for (raw) H-address of 382–385. The energy spectra are calculated from grade 0 events of both bright data and dfe-corrected faint data. The bright data were obtained when the satellite was night, and hence dfe was expected to be stable. It is clear from the figure that gains are very different even for data collected from adjacent columns. We suspect from this analysis that parallel CTIs are very different from column to column over a chip.

We show in figure 4 the Si line energies calculated from the spectra constructed from single column data. H-addresses of the columns are 344–353 for S0C1 and 380–389 for S1C3. Thus the data cover 10 consecutive columns, which correspond to 1/4 arcmin. This is much smaller than the HPD of XRT and the change of spectral parameters should have instrumental origin (not intrinsic to the source). Standard deviations of the line center energies shown in figure 4 gives 22 eV for S0C1 and 48 eV for S1C3. Because the line center shift due to the parallel CTI is very roughly 20 eV, this means that relative variations of the parallel CTI from column to column amount to 100 %.

4 Degradation of energy resolution

We calculated the widths of Si, S and Fe lines of Cas A as a function of observation time to evaluate the energy resolution degradation. The data used here are basically same as those shown in figure 1. All these data were taken at the same pointing position of the standard chips, and were corrected for dfe and echo. The lines are intrinsically broad and hence line width itself has little meaning. Measured line widths of Si, S and Fe are listed in table 3.

Table 3: Width of Si, S and Fe lines of Cas A

Sensor	Element	CTI corr.	1993 August	1994 July	1995 August
SIS-0	Si	yes	20.6±1.6	31.4±1.2	39.9±1.2
		no	20.3±1.6	32.0±1.4	40.2±1.4
	S	yes	33.3±2.5	42.1±1.9	52.4±2.2
		no	33.2±3.0	42.7±1.9	50.2±2.2
	Fe	yes	99.7±10.3	114.5±8.7	125.6±9.1
		no	99.1±10.3	115.0±8.8	116.4±8.8
SIS-1	Si	yes	21.8±1.0	33.4±1.2	43.5±1.3
		no	22.2±1.2	36.0±1.3	44.9±1.5
	S	yes	32.5±1.5	44.0±2.2	53.8±2.6
		no	32.4±1.7	44.8±2.2	52.8±2.3
	Fe	yes	87.4±7.7	107.2±9.0	125.4±10.7
		no	87.5±7.8	104.2±9.1	118.2±10.3

1. Line widths listed are σ of a gaussian model function in unit of eV and their errors are in 90% confidence limit.
2. Approximate line center energies are 1.85 keV (Si), 2.44 keV (S) and 6.58 keV (Fe).

We showed in the table the line widths obtained before and after CTI correction. As seen from the table, CTI correction does not improve the energy resolution. This confirms that non-uniformity of CTI is very large and the small scale CTI variations are comparable to the CTI itself.

Time variations of the line width may be fitted by the following model function:

$$\sigma_{obs} = \left\{ \sigma_{intr}^2 + (\alpha t)^2 \right\}^{1/2}, \tag{1}$$

where σ_{obs} is the observed line width in unit of eV, σ_{intr} the intrinsic line width in eV, t time after the launch, α the energy resolution degradation coefficient. This model assumes that the CTI increase linearly with time after the launch. We found that this model can reproduce the apparent change of the line width relatively well. Best fit models to the CTI corrected data are plotted in figure 5 and the optimized parameters are listed in table 4. Parameters listed in the table are

Table 4: Best fit parameters of apparent line width change

Element	SIS-0		SIS-1	
	σ_{intr} (eV)	α (eV/year)	σ_{intr} (eV)	α (eV/year)
Si	20±2	14±3	22±2	16±3
		(0.77±0.16)		(0.85±0.15)
S	33±2	17±3	33±2	18±4
		(0.69±0.11)		(0.73±0.15)
Fe	100±2	31±9	88±2	37±9
		(0.48±0.14)		(0.56±0.13)

Values in the parenthesis are α divided by the line center energy, and are represented in unit of %/year.

consistent between S0 and S1 except for the intrinsic line width of iron. The reason of the different intrinsic line width of iron is not known. As seen from the table, α is not proportional to the line energy (α divided by line center energy is not same for Si, S and Fe). Although this might be interpreted that CTI is not constant against the photon energy, it could be due to a systematic effect in the course of model fitting. Si and S lines are complex and they are not fully resolved especially in 1995 data. Thus the apparent line widths we obtained may not be completely free from systematics and such systematics may have produced energy dependence of α (in unit of %/year).

Due to the non-uniformity of CTI, energy resolution of SIS has significantly degraded. At the energy of Si line (1.85 keV), resolution was 72 eV (FWHM) at launch and is now (2.5 year after the launch) ∼110–120 eV. Energy resolution at Fe line (6.58 keV) was 130 eV (FWHM) at launch and is now ∼220–250 eV. From the same reason, even intrinsically narrow line produces artificial line width. The artificial line widths (σ) at present (2.5 year after the launch) would be ∼40 eV for Si and ∼80–90 eV for Fe.

5 Discussion

We found that parallel CTI is significantly non-uniform over a chip. Although we investigated only the global and column to column variations of CTI, it is suspected that CTI in general is not

uniform in nature. Probably the amount of charge lost in the course of charge transfer fluctuates very largely from pixel to pixel.

It is generally accepted that charge traps produce CTI. Even if the traps are distributed uniformly over a chip, amount of charge lost by the transfer fluctuates according to the Poisson statistics. Simple estimation shows that this Poisson fluctuation is negligibly small at present. For example, a charge packet of 6.4 keV photon will loose about 50 electrons due to CTI (August 1995). Poisson fluctuation of this electron lose, which corresponds to $\sim 20-30$ eV, will degrade the energy resolution from 130 eV to $\sim$133 eV. This is much smaller than the energy resolution degradation discussed here.

Due to the non-uniformity of CTI, current CTI correction algorithm is not working as expected. It does not restore the degradation of the energy resolution due to CTI. Because the non-uniformity is very large and the CTI varies probably from pixel to pixel, we need to define the CTI for each pixel to restore the original energy resolution. This is equivalent to define the gain for each pixel and hence practically impossible for SIS.

Because we cannot correct non-uniform CTI for the data, only the method we can adopt is to include it in the response matrices of SIS. This may be possible by changing Fano factor. This means that Fano factor becomes in general a function of energy and time. However, the small energy dependence of α (see table 4) seems to have right tendency reproduced by constant Fano factor. We may be able to assume that fano factor is a function of only observation time. A little more analysis is needed to confirm this point, but it makes calibration and software simpler if we can assume that Fano factor depends only on observation time. Even using the Fano factor adjusted matrices, it will still be needed to apply CTI correction to the data just to adjust the gain.

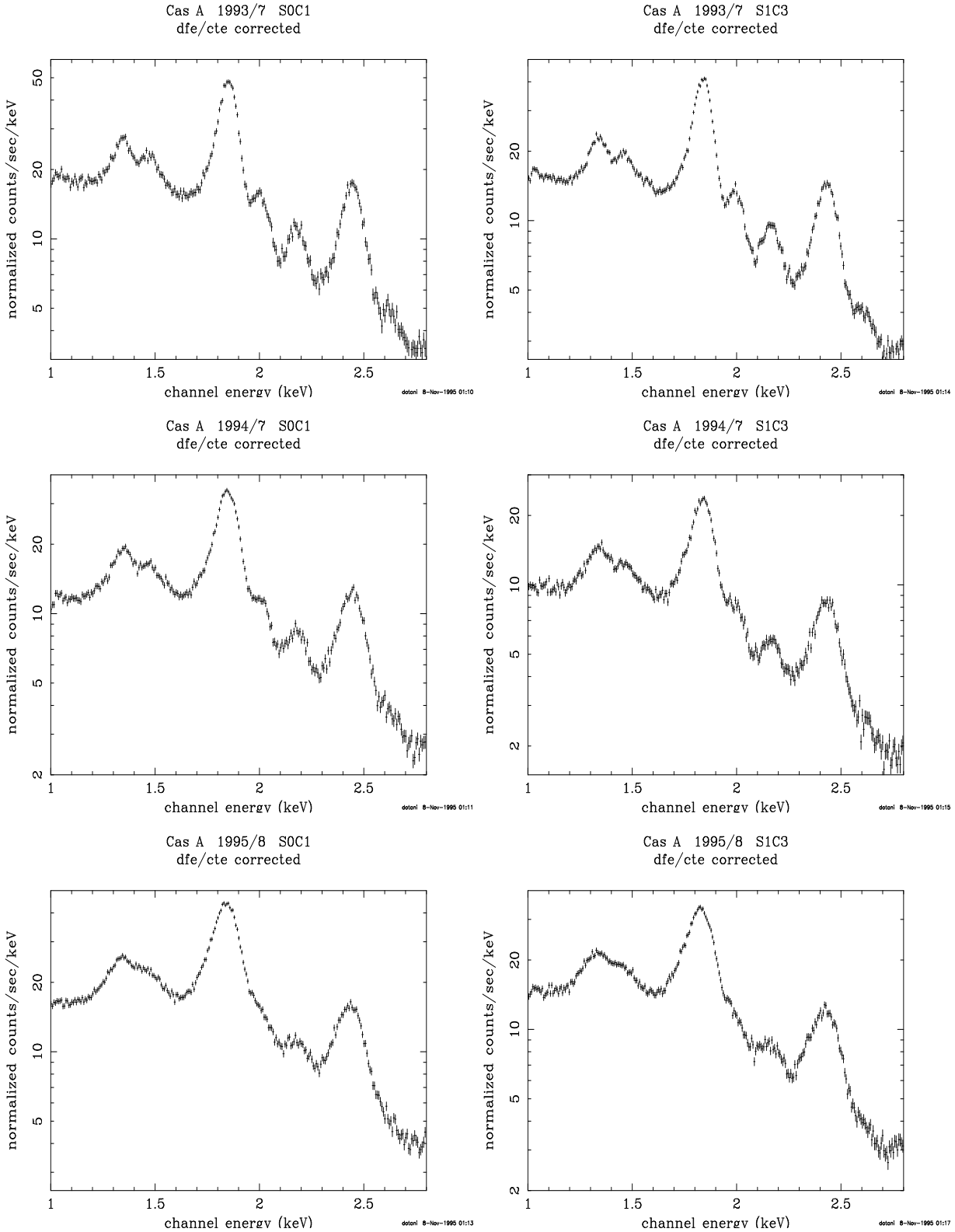

Figure 1: Cas A spectra on three occasions: August 1993, July 1994 and August 1995. The spectra were calculated from the data in 1 ccd faint mode and were corrected for DFE and CTI. Degradation of the energy resolution with time is clear.

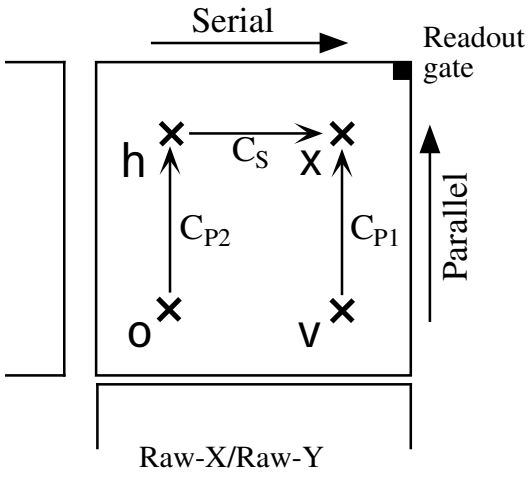

Figure 2: Pointing positions of the standard chips in 1995 Cas A observations. Using these 4 pointings of data, we can determine two parallel CTIs, C_{P1} and C_{P2}, independently.

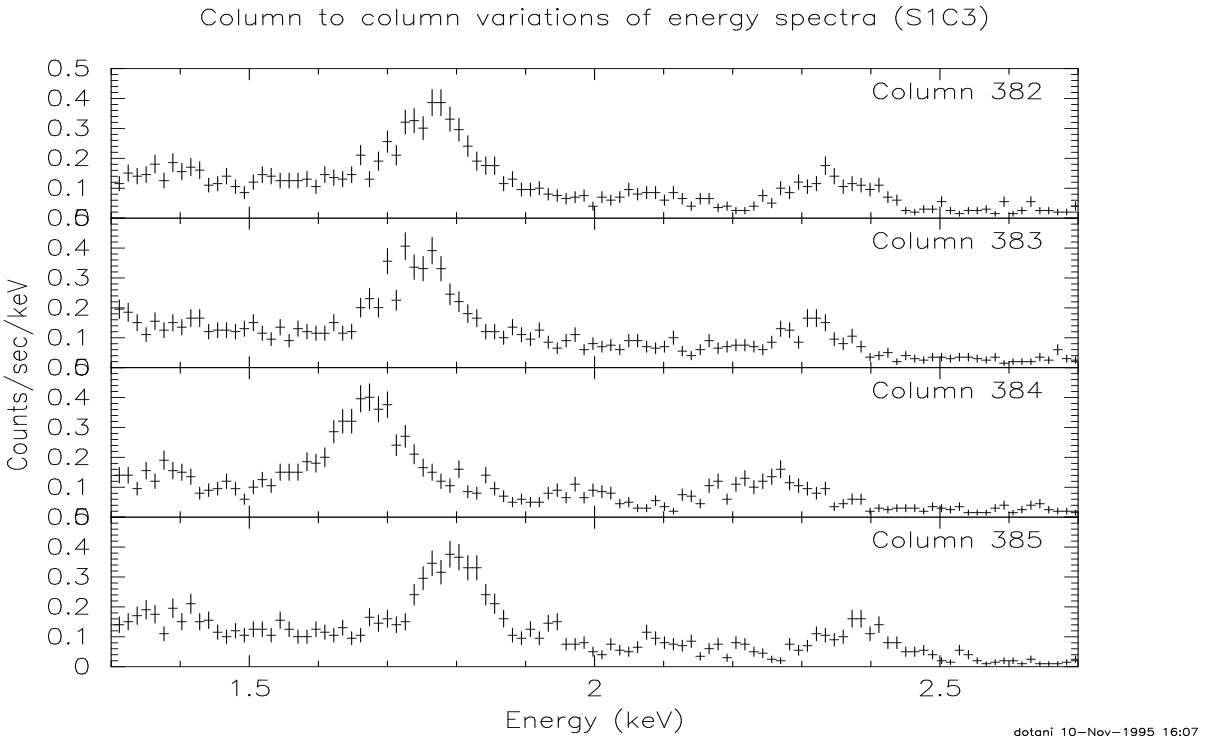

Figure 3: Energy spectra of Cas A calculated from the data from a single column. The data used were grade 0 events of bright and dfe-corrected faint mode data, and were not corrected for CTI. It is clear from the figure that variation of apparent gain between columns is very large even for the adjacent columns.

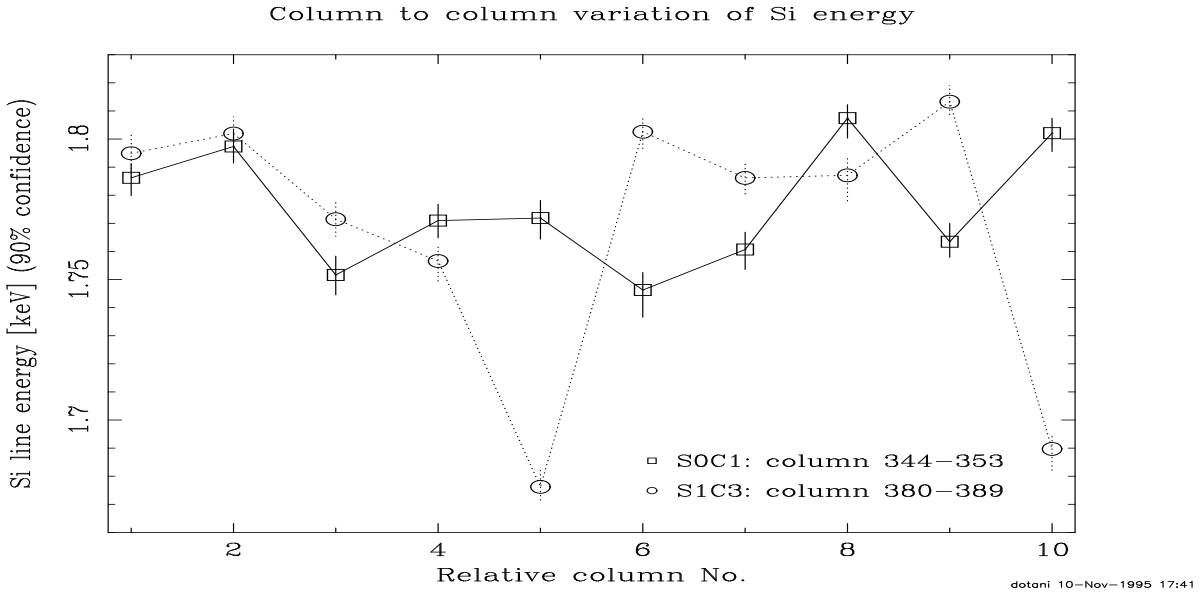

Figure 4: Si line energis obtained from the single column energy spectra. Variations of the line center energies are due to column to column variations of parallel CTI.

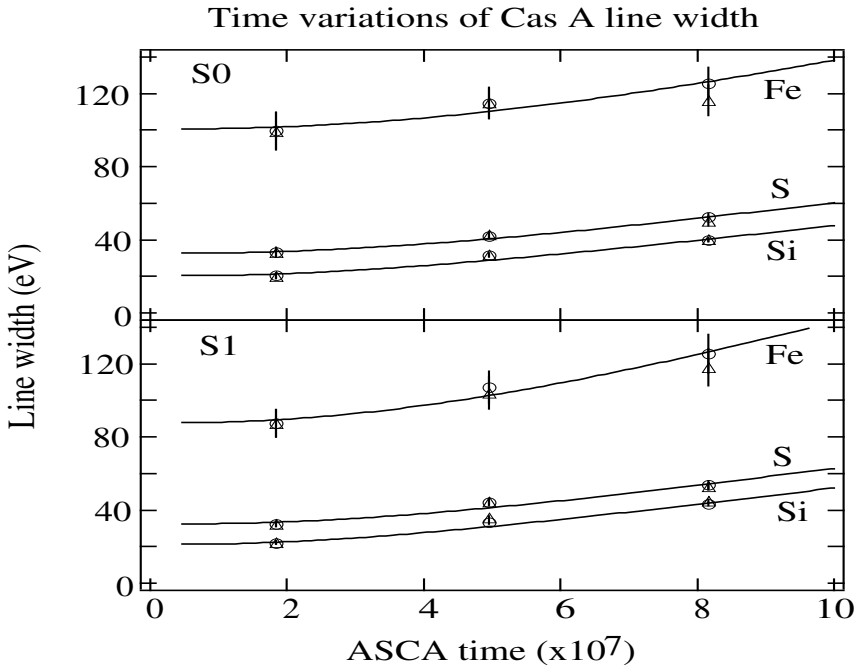

Figure 5: Time variations of the apparent line widths of Cas A and the best fit model function. Circles represent CTI corrected data and triangles represent data not corrected for CTI. Model function is fitted to the CTI-corrected data. ASCA time of the launch is 0.432×10^7 sec.