Performance of the Charge-Injection Capability of Suzaku XIS

Hiroshi Nakajima, Hiroya Yamaguchi, Hironori Matsumoto, Takeshi Go Tsuru, and Katsuji Koyama

Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa, Oiwake-cho, Sakyo-ku, Kyoto 606-8502

Hiroshi Tsunemi, Kiyoshi Hayashida, Ken’ichi Torii, Masaaki Namiki, Satoru Katsuda, Masayuki Shoji, Daisuke Matsuura, and Tomofumi Miyauchi

Department of Earth and Space Science, Graduate School of Science, Osaka University, Machikaneyama-cho, Toyonaka, Osaka 560-0043

Tadayasu Dotani, Masanobu Ozaki, and Hiroshi Murakami

Institute of Space and Aeronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510

Mark W. Bautz, Steve E. Kissel, Beverly LaMarr, and Gregory Y. Prigozhin

Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA

(Received 2007 January 8; accepted 2007 March 8)

Abstract

A charge-injection technique is applied to the X-ray CCD camera, XIS (X-ray Imaging Spectrometer) aboard Suzaku. The charge transfer inefficiency (CTI) in each CCD column (vertical transfer channel) is measured by the injection of charge packets into a transfer channel and subsequent readout. This paper reports on the performances of the charge-injection capability based on the ground experiments using a radiation-damaged device, and in-orbit measurements of the XIS. The ground experiments show that charges are stably injected with a dispersion of 91 eV in FWHM in a specific column for the charges equivalent to an X-ray energy of 5.1 keV. This dispersion width is significantly smaller than that of the X-ray events of 113 eV (FWHM) at approximately the same energy. The amount of charge loss during transfer in a specific column, which is measured with the charge-injection capability, is consistent with that measured with the calibration source. These results indicate that the charge-injection technique can accurately measure column-dependent charge losses, rather than the calibration sources. The column-to-column CTI correction to the calibration source spectra significantly reduces the line widths compared to those with a column-averaged CTI correction (from 193 eV to 173 eV in FWHM on an average at the time of one year after the launch). In addition, this method significantly reduces the low-energy tail in the line profile of the calibration source spectrum.

Key words: instrumentation: detectors — techniques: spectroscopic — X-rays: general

1. Introduction

The high positional and moderate energy resolutions of the Charged Couple Device (CCD) established this device to be the main detector for imaging spectroscopy in X-ray astronomy since ASCA/SIS (Burke et al. 1993). However, one drawback to an X-ray CCD in-orbit is degradation of the gain and energy resolution due to an increase of the charge transfer inefficiency (CTI). The proton irradiation on the CCD chip increases the number of charge traps in the CCD, which is composed of silicon crystals. This defect is more severe for low-energy protons because they deposit more energy than high-energy protons in the CCD transfer channel. The main origin of the CTI and consequent gain degradation is the increase of charge traps. In fact, Chandra/ACIS has suffered from a degraded energy resolution due to low-energy (≈ 10–100 keV) protons in the van Allen belts (Plucinsky et al. 2000). Although a thick shielding around the CCD camera can significantly reduce the proton flux on the CCD, the radiation damage cannot be ignored over a mission lifetime of several years.

In order to maintain the good performance of CCDs in orbit, the CTI must be frequently measured and applied to the data. Most of the major X-ray missions are provided with one or more calibration sources to measure the CTI. The number of charge traps is not uniformly distributed over the CCD imaging area, and hence the CTI is also not uniform over the imaging area. Therefore, the CTI correction should be independently executed for each column (vertical transfer channel). However, the limited flux of calibration X-rays impedes an accurate and frequent measurement of the CTI and its spatial variation over the imaging area.

Recently a charge-injection technique has been developed (Prigozhin et al. 2004; Bautz et al. 2004; LaMarr et al. 2004; Smith et al. 2004; Meidinger et al. 2000). A charge packet with the amount of Q is artificially injected through a charge-injection gate (Tompsett et al. 1975) into each column, and is subsequently readout as Q′ after charge transfer in the same manner as the X-ray event. This method allows us to measure the charge loss (δQ = Q – Q′) for each column, which in turn can potentially be a powerful tool for CTI calibration.

The X-ray Imaging Spectrometer (XIS: Koyama et al. 2007 and references therein) aboard the Japanese 5th X-ray satellite Suzaku (Mitsuda et al. 2007) is equipped with a charge-injection structure (Prigozhin et al. 2004; Bautz et al. 2004; LaMarr et al. 2004). The low-Earth orbit makes the detector background of the XIS lower and more stable than those of Chandra and XMM-Newton. However, the XIS’s gain and energy resolution have gradually degraded due to an increase of the CTI during transit through the South Atlantic Anomaly. After six months from the first-light of the XIS, the CTI has...
increased to a non-negligible level. This result has stimulated us to investigate the in-orbit charge-injection performances. This paper reports on the results. Sections 2 and 3 of this paper describe the XIS and charge-injection capability.

Section 4 is devoted to CTI experiments, while section 5 describes the results of the ground and onboard experiments. A discussion and a summary are in sections 6 and 7, respectively. The mean ionization energy of an electron by X-rays in silicon is assumed to be 3.65 eV e\(^{-1}\) throughout this paper.

2. The CCDs of the XIS

Koyama et al. (2007) have provided details on the XIS and CCDs (MIT Lincoln Laboratory model CCID41). Hence, we briefly duplicate that for the charge-injection study of this paper. The CCDs are the three-phase frame transfer type, and have basically the same structure as those of Chandra/ACIS. Each pixel size is 24 \(\mu\)m \(\times\) 24 \(\mu\)m, and the number of pixels is 1024 \(\times\) 1024 in the imaging area. Therefore, the size of the imaging area is \(\sim 25\) mm \(\times\) 25 mm. The exposure time is 8 s for the normal clocking mode. With radiative cooling and a Peltier cooler, the CCD temperature is controlled to \(-90^\circ\)C. Hence, the dark current is suppressed to \(\sim 2\) electrons/8 s/pixel. Four CCDs are aboard Suzaku. Three of them are front-illuminated (FI) chips, while the other is a back-illuminated (BI) chip. The BI chip has the same basic specifications as the FI chips, except that the BI chip has a larger quantum efficiency in the soft energy band. Ground calibrations verified that the thickness of the depletion layer is \(\sim 65\) \(\mu\)m for the FI chips, and \(\sim 42\) \(\mu\)m for the BI chip. In order to see the function of the CCD, we give a schematic view of the XIS FI chip in figure 1. Each CCD chip has four segments (from A to D), and each segment has one readout node. \(^{55}\)Fe calibration sources, which irradiate the upper edge of segments A and D, are used for monitoring the gain, CTI, and energy resolution in orbit.

3. The Charge Injection

Prigozhin et al. (2004) have reported details concerning the charge-injection structure. While referring to figures 1 and 2, we here describe the essential function of charge injection. For brevity to describe the charge-injection technique and its results, notations of the parameters that are frequently used in this paper are listed in Table 1.

A serial register of 1024 pixels long is attached next to the upper edge of the imaging area (hereafter, we call this the charge-injection register). An input gate is equipped left of the charge-injection register (see figure 1). Pulling down the potential for electrons at the input gate and the next electrode (S3 in figure 2), the potential well is filled with charges with an amount of \(Q\). Then, pulling up the potential, the charge packet is spilled. The amount of charge is controlled by the offset voltage between the input gate and the next electrode (S3). In normal XIS operations, this fill-and-spill cycle is repeated every 1/40960 s \(\simeq\) 24 \(\mu\)s. The deposited charge packets (\(Q\)s) in the charge-injection register are vertically transferred into the imaging area by the same clocking pattern as that of X-ray events. A part of the packet (\(\delta Q\)) will be trapped by the charge traps during the transfer. After the launch, because \(\delta Q\) is not negligible, due to the increase of charge traps, only \(Q\) can be measured with the injection of a single charge packet and the normal readout. On the other hand, we need a measurement of \(\delta Q\) in order to estimate the CTI. We hence adopt the following injection pattern, with which we can obtain both values of \(Q\) and \(\delta Q\) simultaneously, as shown in the left panel of figure 3.

After injecting a test charge packet of \(Q\) in one row (horizontal transfer channel), we inject packets with the same amount of \(Q\) in five subsequent rows: the preceding four packets are called sacrificial charge packets, and the last one is the reference charge packet. The test charge packet is separated from trains of sacrificial charge packets to allow the event-detection algorithm (Koyama et al. 2007).

The test charge packet may suffer from traps in the transfer channel (column), and therefore the readout charge (\(Q_{\text{test}}\)) should be \(Q - \delta Q\). On the other hand, since the preceding sacrificial charge packets may fill the charge traps, the subsequent reference charge packets may not be trapped if the clocking time is shorter than the de-trapping time scale (Gendreau et al. 1993). Thus, the readout charge (\(Q_{\text{ref}}\) from the reference charge packet should approximately equal to \(Q\). The right panel of figure 3 shows a frame image taken during our experiments. The positions of the charge packet trains are periodically shifted by one column to allow the proper event-detection algorithm. The sacrificial charge packets are not read for the same reason. The value \(\delta Q\) after the transfer can be measured by subtracting the mean pulse height amplitude (PHA) of the test events from that of the reference events. By selecting different \(Qs\), we can also investigate the relation between \(Q\) and \(\delta Q\).
Fig. 2. (Left panel) Schematic view of the charge-injection structure. Charge packets are injected to the charge-injection register from an input gate located at the edge of the register. After depositing the packets over the register, a vertical clock runs to inject the packets into the imaging area. (Right panel) Schematic view for the injection of charges at the input gate. The offset voltage between the input gate and the S3 electrode can control the amount of injected charge ($Q$). These figures are adopted from Bautz et al. (2004).

Table 1. The notation list of parameters.

| Parameters                                      | Notation         |
|------------------------------------------------|------------------|
| Injected charge (for one column)                | $Q$ ($Q_{COL}$) |
| Readout charge (for one column)                 | $Q'$ ($Q_{COL}'$) |
| Charge loss in the transfer (for one column)    | $\delta Q$ ($\delta Q_{COL}$) |
| Charge Transfer Inefficiency (for one column)   | CTI ($CTI_{COL}$) |
| Column-dependent CTI obtained with charge injection | $CTI_{CI}$ |
| Column-averaged CTI obtained with the calibration source | $CTI_{CAL}$ |

Fig. 3. (Left panel) Schematic view of how to measure $\delta Q$ using the test and reference charge packets. The amount of lost charge ($\delta Q$) can be estimated by comparing the PHA of the test packet, which suffers from CTI, to that of the reference packet, which is not affected by the traps. (Right panel) Frame image of the XIS during the charge-injection experiment. The gray scale shows the pixel level, not the number of events. There are two events per each column: The lower one is the test event and the upper one is the reference event. Note that the sacrificial packets are not displayed at the request of the event detection algorithm.
4. Ground and In-Orbit Experiments

4.1. Ground Experiments

Before the launch of Suzaku, we conducted ground experiments with the same type of CCD chip as the XIS in order to verify the performance of the charge-injection function. The CCD chip was damaged by protons utilizing the cyclotron at the Northeast Proton Therapy Center at Boston (USA). A proton beam of 40 MeV was irradiated on the circular region shown in figure 4. The total fluence was 2.0 \( \times 10^9 \) cm\(^{-2}\), which is approximately the same as that the XIS may receive during several years in orbit. Experiments with damaged and non-damaged chips were conducted at MIT and Kyoto University, respectively, using a fluorescent X-ray generation system (Hamaguchi et al. 2000 for the latter) and a \(^{55}\)Fe radioisotope. During these experiments, the sensors were maintained at a pressure of \( \sim 10^{-5} \) Torr and a CCD temperature of \( \sim 90^\circ \)C. In this paper, we report on the results concerning the FI chip, because the quantitative differences between the FI and BI chips are small.

4.2. In-Orbit Experiments

In-orbit charge-injection experiments were conducted during observations of the supernova remnant (SNR) 1E 0102–72.3 in the Large Magellanic Cloud. All of the data were acquired with the normal clocking mode and with the 3 \( \times 3 \) or 5 \( \times 5 \) editing modes (Koyama et al. 2007). We applied several values of \( Q \) in order to investigate the dependence of \( \delta Q \) on \( Q \). Table 2 summarizes the experimental logs.

### Table 2. Log of the charge-injection experiment in orbit.*

|                | XIS 0 & XIS 2 | XIS 1 & XIS 3 |
|----------------|--------------|--------------|
| Date           | 2006/7/17    | 2006/6/26–27 |
| Time           | 06:06:50–21:39:46 | 02:47:07–02:37:55 |
| The equivalent X-ray energy of the injected charge packets (keV) | 0.6/4.2/8.0 for XIS 0 | 0.3/7.3 for XIS 1 |
| The equivalent X-ray energy of the injected charge packets (keV) | 0.6/3.9/7.8 for XIS 2 | 0.5/4.6 for XIS 3 |
| Total effective exposure (ks) | 6.0 | 5.2 |

* The XIS 1 is the BI chip and the others are the FI chips.

![Fig. 4. Frame image of the proton-damaged FI chip used in the ground experiments. The gray scale is the pixel level, not the number of events.](image)

Gaps between segments are horizontal over-clock regions. The chip is different from those in other regions due to the dark current.

5. Measuring the Charge Loss for Each Column

5.1. Stability of the Amount of Injected Charge

In order to reliably estimate \( \delta Q \), \( Q \) in reference and test events must be equal, because \( \delta Q \) is the difference between \( Q'_{\text{ref}} \) and \( Q'_{\text{test}} \). If \( Q \) can be controlled more accurately than the injected charge dispersion in each column, charge injection offers obvious advantages over conventional CTI measurements using X-ray calibration sources. We hence checked the stability of \( Q'_{\text{test}} \) when a designed offset voltage was applied at the input gate. For this propose, we used a non-damaged chip, because \( Q'_{\text{test}} \) should be nearly equal to \( Q \), due to the negligible number of charge traps. Figure 5 shows the spectra of fluorescent X-rays (Ti K\( \alpha \)) collected on the ground, and \( Q'_{\text{test}} \) of approximately the same equivalent energy as X-rays collected both on the ground before proton damage and in orbit after damage. Events were extracted from one arbitrary column for all data sets. The FWHM of the \( Q'_{\text{test}} \) was 91 \( \pm 4 \) eV for ground data and 95 \( \pm 6 \) eV for in-orbit data, that are significantly better than that of the X-ray data of 113 \( \pm 7 \) eV. The former FWHMs mean the stability of \( Q_{\text{COL}} \) of charge injection under the controlled offset voltage at the input gate, and the latter is primarily due to the Fano noise. Thus, we verified that \( Q_{\text{COL}} \) is sufficiently stable to estimate \( \delta Q_{\text{COL}} \).

Next, we consider whether the ratio of \( Q'_{\text{test}}/Q'_{\text{ref}} \) is proportional to the CTI, which is measured with the \(^{55}\)Fe calibration X-rays. PHA histograms of \( Q'_{\text{test}} \) and \( Q'_{\text{ref}} \) are fitted with a single Gaussian for each column. For the \(^{55}\)Fe events, we extract the events from the upper and lower 100 rows of the imaging area (\( Q'_{\text{55Fe,upper}} \) and \( Q'_{\text{55Fe,lower}} \)). The 100 rows are selected for the statistical point of view in the spectral fitting. Figure 6 shows the correlations between \( Q'_{\text{test}}/Q'_{\text{ref}} \) and \( Q'_{\text{55Fe,upper}}/Q'_{\text{55Fe,lower}} \). For non-damaged chip (the left
panel), because \( \delta Q \) during parallel transfer is 0 or 1 electron, a correlation can hardly be seen. For a damaged-chip, on the other hand, the increase of CTI is significant in the circular region, as shown in figure 4. We can see a clear positive correlation between the \( ^{55}\text{Fe} \) and charge-injection events, especially in segments A, B, and C. The best-fit slope is \( \sim 1.05 \) and the correlation coefficient is 0.94 (d.o.f. = 976). Hence, \( Q_/test/Q_/ref \) properly reflects the CTICOL.

5.2. Measuring and Compensating the Charge Loss

Based on the verification for the charge-injection technique described in subsection 5.1, we applied this technique to the onboard data.

Figure 7 shows the PHA distribution for \( Q_/test/Q_/ref \) (open circle) and \( Q_/test/Q_/ref \) (cross) as a function of the \( X \)-coordinate (column). \( \delta Q_/COL \) was clearly observed in orbit for the first time. In order to estimate the \( \delta Q \) dependance on \( Q_/ref \), we selected two or three different \( Q_/ref \) values for the in-orbit charge injection experiment (table 2). Assuming a single power-law function of \( \delta Q \propto Q_/ref^\alpha \), as in Grant et al. (2004), we derived \( \alpha \) for each column. The results are given in figure 8. The weighted mean values of \( \alpha \) are 0.62, 0.71, 0.62, and 1.00 for the XIS 0, 1, 2, and 3, respectively. These values are roughly consistent with another ground experiment (Prigozhin et al. 2004).

The charge-injection data provide only information on \( \delta Q \) at the edge of the imaging area, and hence we need to know the \( Y \) coordinate dependance of \( \delta Q \) from the data of celestial objects that extend over the field of view of the XIS. Figure 9 shows the center energy of the 6.4 keV line as a function of the \( Y \) coordinate for diffuse X-rays from the Sgr C region (Obs.Sequence = 500018010, Obs.Date = 2006-02-20). The line center at the lower edge of the image (\( Y = 0 \)) deviates from 6.40 keV due to the CTI during the fast transfer of all data in the imaging area to the frame-store region (hereafter, we call this frame-store-transfer). However, the origin of the deviations at the other image regions is complicated because the charges suffer from three kinds of CTI: the CTI in the imaging area due to the frame-store-transfer, that in the frame-store region due to the frame-store-transfer and that in the frame-store region due to subsequent slow vertical transfer. The CTI during horizontal transfer was ignored in this work. The CTI depends on the
Fig. 7. PHA distribution of the test (crosses) and reference (open circles) events as a function of the $X$ coordinate of the XIS 3 for two different $Q$s. The equivalent energies of these $Q$s are shown in table 2. Note that because each segment has its own readout transistor and analog-to-digital converter, the gain varies from segment to segment, and hence the PHA level varies. Anomalous columns including a hot or flickering pixel are eliminated.

Fig. 8. Distribution of the power-index ($\alpha$) in the relation of $\delta Q \propto Q^\alpha$ (XIS 3) as a function of the $X$ coordinate, which is obtained through charge-injection experiments with the various charge amounts given in table 2. Some anomalous columns were eliminated. The typical error indicates the one-sigma confidence level.

number density of charge traps and the transfer speed (Hardy et al. 1998). The shielding depth and pixel size are different in the imaging area and the frame-store region. The CTIs may therefore be different between these areas. However, we cannot estimate each CTI component separately from the total CTI seen in figure 9.

Due to this limitation, we assume the following phenomenological compensation of the charge, as shown in figure 10. The charge loss during transfer is assumed to consists of a component depending on $Y$ ($\delta Q_1$) and a $Y$-independent one ($\delta Q_2$). Both components are proportional to $Q^\alpha$, but their proportionality constants may be different from each other. Considering that the $Q$ is generated by X-rays absorbed at $Y$, the column-averaged charge loss of $\delta Q(Y)$ is given by

$$\delta Q_1 = A_1 \times Q^\alpha, \quad \delta Q_2 = A_2 \times Q^\alpha.$$  

(1)

$$\delta Q(Y) = \left[ \delta Q_1 \times \frac{Y}{1023} + \delta Q_2 \right].$$  

(2)

$A_1$ and $A_2$ can be estimated from figure 9. We next determined the column-dependent charge loss of $\delta Q_{COL}(Y)$, so that the following relation holds at any $Y$ coordinate:

$$\delta Q_{COL}(Y) = \delta Q(Y) \times \frac{\delta Q_{COL}(1023)}{\delta Q(1023)},$$  

(3)

where $\delta Q_{COL}(1023)$ can be estimated from figure 7. Hence, we can correctly compensate charge over the entire region of the imaging area.
5.3. Energy Resolution

Without a CTI correction, the energy resolution gradually decreases at a rate of \( \approx 50 \text{eV} \) in FWHM at 5.9 keV per year. Using the \( \delta Q_{\text{COL}} \) determined with the charge injection experiment, we make the new spectra for the calibration sources in the observation given in table 2. Figure 11 shows the calibration source spectra after the CTI\(_{\text{CI}}\) (upper) and CTI\(_{\text{CAL}}\) (lower) correction. The tail component after the CTI\(_{\text{CI}}\) correction is significantly reduced compared to that after the CTI\(_{\text{CAL}}\) correction. This strongly indicates that the origin of the tail component is the dispersion of the CTI\(_{\text{COL}}\) among the columns. Hence, the temporal variation in the response function can be suppressed by the charge-injection technique. Figure 12 shows the FWHM of the calibration source spectra after the CTI\(_{\text{CI}}\) and CTI\(_{\text{CAL}}\) corrections. On average, the FWHM was significantly improved from 193 eV to 173 eV. These are the first in-orbit results for the charge-injection function.

Our final purpose is to demonstrate that the \( \delta Q_{\text{COL}} \) parameters are effective for celestial objects. We applied the \( \delta Q_{\text{COL}} \) parameters to the Tycho’s SNR data (Obs.Sequence = 500024010, Obs.Date = 2006-06-27). Figure 13 shows the spectra around the He-like Si Ka emission line in the west part of Tycho’s SNR for the XIS 3 after a CTI\(_{\text{CI}}\) correction and a CTI\(_{\text{CAL}}\) correction. We can see the same benefit as shown in figure 11. Note that the latter is multiplied by 0.8 to avoid confusion. Radiation damage continuously increases while in orbit, and hence the benefit of the charge-injection technique will become more apparent over time, as shown in this figure.
6. Discussion

Because the $\Delta Q_{\text{COL}}$ correction parameters are time dependent, $\Delta Q_{\text{COL}}$ must be periodically measured. We made two sets of $\Delta Q_{\text{COL}}$ using $\Delta Q_{\text{COL}}$ derived from the charge-injection experiment in 2006 May and July, and applied them to the calibration source data taken in 2006 May for XIS 0 and XIS 2. The results are shown in figure 14. The average CTI in July was normalized to that in May, while the relative variation in $\Delta Q_{\text{COL}}$ is preserved. However, the observation times of the charge injection and $^{55}\text{Fe}$ data differ by two months, the FWHM is significantly degraded only for the brightest calibration source. This confirms that, in a practical sense, an interval of two months between each CTI measurement is sufficient, because there are few celestial objects that have emission lines brighter than this calibration source.

Although the charge-injection technique significantly improves the energy resolution of the calibration source spectra, the FWHMs, as shown in figure 12, are still larger than those before the launch (130 eV). Because charge trapping is a probability process, the number of trapped electrons ($\Delta Q$) may also have a probability deviation, which would increase the line width after the transfer. Hence, the CTI correction with the charge-injection technique cannot completely restore the line broadening. We confirm this effect in figure 15, which shows the FWHM of the charge-injection reference events and those of the test events before and after charge compensation for the XIS 3 in-orbit data. In addition, the test events measured on the ground (before the radiation damage) are shown. The smaller FWHMs in all segments of the reference events are due to the fact that the reference events may not lose charge because the charge traps are already filled by the sacrificial events. In fact, the FWHMs of the reference events are consistent with those of the test events collected on ground, although segment D shows an anomalous trend.

Another characteristic of figure 15 is that the FWHMs increase along with the $X$ coordinate for the reference events and test events collected on the ground. This is due to the CTI in the charge-injection register. This influences the accuracy of the mean PHA of the reference events, and hence the accuracy of $\Delta Q$. However, the CTI in the charge-injection register is rather lower than that in the imaging area and frame-store region, because the charge packets are injected with an interval of 3 pixels, and hence they can work as sacrificial charges (Gendreau 1995). In fact, as shown in figure 12, there is no significant difference between segments A and D for improving the FWHM of the calibration source spectra.

These results lead us to use the charge-injection capability to fill the traps in the transfer channel by periodically injecting of $Q$. A ground experiment shows that charges were injected into every 54th row improve the energy resolution (Bautz et al. 2004). We are trying to utilize this charge-injection technique for onboard observations. The results will be presented in a separate paper.

7. Summary

The results of ground and in-orbit experiments concerning the charge-injection capability of the XIS are as follows:

1. The amount of injected charge ($Q$) is sufficiently stable (dispersion of 91 eV in FWHM), which should be compared to the X-ray energy resolution (FWHM of 113 eV) with the same amount of charge.
2. The CTI depends on PHA of the charge. The charge loss can be explained as $\Delta Q \propto Q^{0.62-1.00}$.
3. With the $\Delta Q_{\text{COL}}$ correction, the energy resolution (FWHM) of $^{55}\text{Fe}$ is improved compared to that with the $\Delta Q_{\text{COL}}$ correction (from 193 eV to 173 eV on average) at the time of one year after the launch, and the tail component in the line profile is also significantly reduced.
4. The improved charge-compensation method is applied to Tycho’s SNR data, which results in the same benefit as the calibration source data.
5. We confirm that the energy resolution can be greatly improved by filling the charge trap. Hence, we are currently trying another in-orbit charge-injection capa-
In the experiment to actively fill the charge traps in the transfer channel by the charge-injection technique, the authors express their gratitude to all members of the XIS team. HN and HY are financially supported by the Japan Society for the Promotion of Science. This work is supported by a Grant-in-Aid for the 21st Century COE “Center for Diversity and Universality in Physics” from Ministry of Education, Culture, Sports, Science and Technology of Japan, and by a Grant-in-Aid for Scientific Research on Priority Areas in Japan (Fiscal Year 2002–2006) “New Development in Black Hole Astronomy”.

References

Bautz, M. W., Kissel, S. E., Prigozhin, G. Y., LaMarr, B., Burke, B. E., & Gregory, J. A., & The XIS Team, 2004, Proc. SPIE, 5501, 111
Burke, B. E., Mountain, R. W., Daniels, P. J., Cooper, M. J., & Dolat, V. S., 1993, Proc. SPIE, 2006, 272
Gendreau, K., 1995, PhD Thesis, Massachusetts Institute of Technology
Gendreau, K., Bautz, M., & Ricker, G., 1993, Nucl. Instrum. Methods Phys. Res., Sect. A, 335, 318
Grant, C. E., Bautz, M. W., Kissel, S. E., & LaMarr, B., 2004, Proc. SPIE, 5501, 177
Hamaguchi, K., Maeda, Y., Matsumoto, H., Nishiuchi, M., Tomida, H., Koyama, K., Awaki, H., & Tsuru, T. G. 2000, Nucl. Instrum. Methods Phys. Res., Sect. A, 450, 360
Hardy, T., Murowinski, R., & Deen, M. J., 1998, IEEE Trans. Nucl. Sci., 45, 154
Koyama, K., et al. 2007, PASJ, 59, S23
LaMarr, B., Bautz, M. W., Kissel, S. E., Prigozhin, G. Y., Hayashida, K., Tsuru, T. G., & Matsumoto, H., 2004, Proc. SPIE, 5501, 385
Meidinger, N., Schmalhofer, B., & Strüder, L., 2000, Nucl. Instrum. Methods Phys. Res., Sect. A, 439, 319
Mitsuda, K., et al., 2007, PASJ, 59, S1
Plucinsky, P. P., & Virani, S. N., 2000, Proc. SPIE, 4012, 681
Prigozhin, G. Y., Burke, B. E., Bautz, M. W., Kissel, S. E., LaMarr, B., & Freytsis, M., 2004, Proc. SPIE, 5501, 357
Smith, D. R., Holland, A. D., Hutchinson, I. B., Abbey, A. F., Pool, P. J., Burt, D., & Morris, D., 2004, Proc. SPIE, 5501, 189
Tompsett, M. F., 1975, IEEE Trans., ED, 22, 305