Crosstalk Analysis of Suprime-Cam FDCCDs Using Cosmic Rays in Dark Frames

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ABSTRACT. We analyzed the crosstalks in the new fully depleted CCDs in the Subaru Prime Focus Camera (Suprime-Cam). The effect is evaluated quantitatively using cosmic rays in dark frames. The crosstalk is well approximated by a linear correlation and the coefficient is $\sim 10^{-4}$. The coefficients are not significantly different among the 10 CCDs. We also find that the crosstalk appears not only in the corresponding pixels but also in the next pixel but one. No crosstalk is detected among different CCDs in Suprime-Cam. Based on the analysis, a correction procedure for the crosstalk is presented, and its application to the data is demonstrated.

Online material: color figures

1. INTRODUCTION

Multi-channel CCDs often suffer from a crosstalk phenomenon between readout channels. There are several user documents describing the crosstalk and some observatories prepare data to correct this crosstalk. Freyhammer et al. (2001) estimated the effect in DFOSC and FORS1 at the ESO VLT. The studies for the Advanced Camera for Surveys (ACS) in the Hubble Space Telescope (HST) are also available (Giavalisco 2004a, b; Suchkov et al. 2010; Suchkov & Baggett 2012).

Since the replacement of the CCDs in 2008 July with fully depleted back illuminated CCDs (FDCCD; Kamata et al. 2008), the data of the Subaru Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) show crosstalk signatures in a CCD. The effect is easily recognized in narrowband data with a low sky background (Fig. 1). As one of the crosstalk dimming regions (shadows) has the same spatial parity as the source, it obtains a higher signal-to-noise ratio (S/N) after coadding (Fig. 2) and causes a problem even in a deep field study.

In this article, we investigated the crosstalk effect in Suprime-Cam in order to remedy this problem. We adopted a method using cosmic rays in dark frames and present a recipe to remedy the crosstalk effects.

2. MODELS AND METHOD

2.1. Suprime-Cam

Suprime-Cam is equipped with 10 FDCCDs, and each FCCCD is read out from four channels. In this article, we call the channels chA, chB, chC, and chD along the $x$-axis of the output Flexible Image Transport System (FITS) file for simplicity. The data from each channel consist of $512 \times 4177$ CCD pixels, $8 \times 4177$ pixels of the prescan region of the serial read, and $48 \times 4177$ pixels of the overscan region of the serial read, followed by $(8 + 512 + 48) \times 48$ pixels overscan of the parallel read. The FITS data have an additional $(8 + 512 + 48) \times 48$ pixels in the prescan region, but these should not be used for the analysis (Fig. 3). The 10 CCDs are arranged in two rows of five CCDs each. The CCDs in the upper row (detector ID = 0,1,2,6,7) are read from the top edge ($y = 4177$), and those in the lower row (detector ID = 3,4,5,8,9) are read from the bottom edge ($y = 1$).

When a CCD is read out, the charges stored in each pixel are converted to a voltage at on-chip amplifiers (on-chip amps) at four channels. The conversion factor of the on-chip amps has an $\sim 15\%$ difference. Suprime-Cam is equipped with 40 preamplifiers (preamps) arranged in 10 quad-channel preamp boards around the camera dewar. One preamp board handles signals from a CCD. The gain of the preamp is three (Nakaya et al. 2008), and the difference among the 40 preamps is $\sim 1\%$ (Nakaya, H. 2012, private communication). The signals are then put into the signal board (SIG), and a correlated double sampling is performed (Nakaya et al. 2012). Suprime-Cam has five

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1 See http://www.noao.edu/kpno/mosaic/manual/mosa_2.html.
2 See http://www.astronomy.ohio-state.edu/MDM/MDM4K/.
3 See http://www.stsci.edu/hst/acs/performance/anomalies/zoo_xtalk.html.
4 See http://www.ast.cam.ac.uk/ioa/research/vdfs/docs/reports/sv/.
5 See http://www.noao.edu/noao/mosaic/calibs.html.
6 See http://www.naoj.org/Observing/Instruments/SCam/ccd.html.
SIG boards, and one SIG board has eight channels. The signals from CCD0 and CCD1 go into the first SIG board, those from CCD2 and CCD3 go into the next, and so on. The signal is then converted into a digital value. The analog-to-digital conversion factor is configured to be one (Nakaya et al. 2008), but slightly differs at each channel by $\sim 5\%$. The total gain of the Suprime-Cam data is the product of the three gains of the components: the gain of the analog-to-digital converter (ADC) in the SIG at each channel ($g_1$), the gain of the preamp ($g_2$), and the gain of the on-chip amp at each channel ($g_3$). A schematic figure is shown as Figure 4.

The charges in the CCDs are read out and converted to digital data simultaneously in 40 channels. For example, when $(x, y)$ of CCD0 is read, $(1024 - x, y)$, $(1024 + x, y)$, and $(2048 - x, y)$ of CCDs in the upper row and $(x, 4178 - y)$, $(1024 - x, 4178 - y)$, $(1024 + x, 4178 - y)$, and $(2048 - x, 4178 - y)$ of CCDs in the lower row are read at the same time.

2.2. Crosstalk in Suprime-Cam

The apparent crosstalk appears as follows: When a bright object is observed at $(x, y)$ in chA, shadows appear at three symmetric positions of saturated stars at $(1024 - x, y)$ in chB, at $(1024 + x, y)$ in chC, and at $(2048 - x, y)$ in chD, which are read out at the same time. Currently, for crosstalk in the same CCD, the pixels read at the same time show an apparent crosstalk. The possible crosstalk across the CCDs and the effect on the adjacent pixels in the same CCD are examined later.

In the three shadows corresponding to $(x, y)$, $(1024 - x, y)$ and $(2048 - x, y)$, can be removed by dithering, as their position in the sky changes when the telescope pointing is changed. However, the movement of the shadow at $(1024 + x, y)$ is the same as the object at $(x, y)$, and if the shadow is larger than the slight differential shift caused by optical distortion at the dithered pointing, the shadow gains S/N when we coadd the dithered images (Fig. 2, right). The existence of a shadow of the same parity is different from quadrantic readout devices, such as ACS/HST and FORS1/VLT. As investigated in a later section, a shadow of the same parity causes problems in deep field.
imaging in broadband, though the effect cannot be detected in a single exposure.

2.3. Signal Variables

If the crosstalk occurs around the input of the on-chip amps, the effect would correlate with the raw charge $v \times (g_1 \times g_2 \times g_3)$, where $v$ is the value in the output FITS file after bias subtraction. If the crosstalk occurs between the output of the on-chip amps and the input of the preamps, the effect would correlate with $v \times (g_1 \times g_2)$, and if it occurs between the output of preamps and the input of ADC, the effect would correlate with $v \times g_1$.

We estimated the relative value of the total gain, $g_1 \times g_2 \times g_3$ and the relative gain of SIG+preamps, $g_1 \times g_2$, and listed them in Tables 1 and 2. The details of the estimation are described in the Appendix. Though we do not have $v_2$ or $v_3$ data, the difference of $g_1$ and $g_1 \times g_2$ is small, since the difference of $g_2$ is only $\sim1\%$ among the 40 preamps.

Using the relative gain values, we obtain three different signal values: $v_1 = v$, $v_2 = v \times (g_1 \times g_2)$, and $v_3 = v \times (g_1 \times g_2 \times g_3)$. The value $v_1$ is the count in the FITS file in ADU; $v_2$ is proportional to the voltage between the on-chip amps and the SIG; and $v_3$ is proportional to the charge in a pixel.

3. ANALYSIS

3.1. Method

We can evaluate the crosstalk by taking the correlation between pixels in channel $X$ and channel $Y$, when the pixel in $X$ has a large count and the pixel in $Y$ has a smaller count (Fig. 5). A linear trend of crosstalk effect was reported in previous studies on other CCDs (e.g., Freyhammer et al. 2001; Suchkov et al. 2010). Under the assumption that the crosstalk is linear to the source, the strength of the crosstalk is measured by the coefficient of proportionality. The coefficients of other

| DET-ID | chA | chB | chC | chD |
|--------|-----|-----|-----|-----|
| 0      | 1.050 | 1.063 | 1.083 | 1.069 |
| 1      | 1.070 | 1.138 | 1.217 | 1.212 |
| 2      | 0.995 | 1.019 | 1.038 | 0.947 |
| 3      | 1.022 | 1.040 | 1.042 | 1.154 |
| 4      | 1.006 | 1.128 | 1.085 | 1.033 |
| 5      | 1.015 | 1 | 0.972 | 1.082 |
| 6      | 1.190 | 0.987 | 0.984 | 1.034 |
| 7      | 0.971 | 1.059 | 1.067 | 0.981 |
| 8      | 1.011 | 1.252 | 1.276 | 1.172 |
| 9      | 0.994 | 1.130 | 1.077 | 1.039 |

*aThe gain is changed in 2010 October. The data are valid for the data before the change.

*b The data are valid for the data after the change.
instruments are about $\sim 10^{-4}$; ACS/HST has a coefficient of $-0.6 \times 10^{-4}$ to $-2.3 \times 10^{-4}$ (Suchkov & Baggett 2012), and FORS1/VLT has a coefficient of $-2.3 \times 10^{-4}$ to $-2.5 \times 10^{-4}$ (Freyhammer et al. 2001). It should be noted that the readout count suffers from the quantization error, and a difference smaller than 1 ADU in a certain pixel is buried in the noise. Since the maximum output is $2^{16} - 1 = 65,535$ ADU in Suprime-Cam, the crosstalk coefficient is meaningful when its absolute value is larger than $1/(2^{16} - 1) \sim 1.5 \times 10^{-5}$.

There are several types of data for measuring the correlation. Freyhammer et al. (2001) used a calibration lamp with a mask on the focal plane and a night sky with standard stars. Suchkov et al. (2010) used dark frames and sky frames. In this work, we only use dark frames and cosmic rays to minimize the error from flat fielding and the background level estimation. The small spatial size of the high count pixels in cosmic rays, even smaller than the point spread function (PSF), enables us to examine the possible spatial extent of the crosstalk shadow over a pixel. Moreover, the FDCCD of Suprime-Cam and the Subaru Telescope have several advantages for using cosmic rays in dark frames. Thanks to the thickness of the FDCCD (250 $\mu$m) and the high altitude of the Subaru Telescope, Suprime-Cam receives a relatively large number of cosmic rays. The dark current is very low, less than 0.6 ADU hr$^{-1}$, and the readout noise is also low, 2–2.5 ADU in rms (Kamata et al. 2008). The acquisition of dark frames does not require either a special instrument setting such as a mask or a telescope time at night. We can take dark frames in the daytime if we can keep the instrument in the dark. On the other hand, the drawback to this method is that it is not easy to obtain enough data of high-value count pixels. For example, we could not investigate the behavior near the full-well region in this study because of the lack of such data.

### 3.2. Data

We used all dark frames with EXPTIME $\geq 120$ s taken between 2008 December 03 and 2011 July 02 (UT)—after the fix of the linearity problem and before the hardware incident of the Subaru. The data are retrieved from the Mitaka Advanced Subaru Telescope ARCHive System (MASTARS)$^8$ and the Subaru Mitaka Okayama Kiso Archive (SMOKA).$^9$ The used frames are summarized in Table 3.

Bias is first subtracted using the median of 48 pixels in the serial overscan region at each $y$. The bias level has an $\sim 2$ ADU varying pattern in the $x$ direction, as shown in Figure 6. This pattern is common in all of the CCDs, in all of the channels, and in all of the exposures as far as we examined in the dark frames. This pattern is corrected using the data in the parallel overscan region. The median of the parallel overscan, after subtraction of the serial overscan of the parallel overscan, reflects the pattern, and it is subtracted from the data in each frame. Finally, the dark is subtracted, and we hereafter call the value after the mean dark subtraction as $v_1$.

The dark level is estimated by averaging the count in a channel, avoiding the pixels which are hit by cosmic rays or are affected by the crosstalk because of a high count in other channels. The mean dark count varies in different CCDs and channels. The typical dark count is 0.16 ± 0.09 ADU for 300 s exposure $((5 \pm 3) \times 10^{-4}$ ADU s$^{-1}$), and the rms is 2.2 ± 0.2 ADU. The rms includes readout noise and the error of bias/overscan subtraction. As the total gain of Suprime-Cam is about $3-4e$ ADU$^{-1}$, the mean dark count is less than 1e.

In the bias and the dark corrected dark images, high count pixels are picked up; then, corresponding pixels in the other three channels in the same CCD are checked. We arbitrarily adopted the threshold of the “high” count as 300 ADUs in $v_1$. A total of 1,277,705 pixels are marked as high count pixels in the 370 frames. The count of the three pixels corresponding to the high count pixel is cataloged. When taking the correlation of $v_1(X)$ as the high count and $v_1(Y)$ as the affected count, $v_1(Y)$ should be corrected for dark count, while $v_1(X)$ should not—since the dark count would also contribute to the crosstalk. However, as we take $v_1(X) > 300$ as the high count in the following analysis, the effect of the dark subtraction of 0.16 ADU creates 0.05% error in the coefficient. The error is negligible, as we estimate the coefficients with three significant figures. For simplicity, we used the bias and the dark subtracted value for $v_1(X)$ instead of the bias subtracted value.

### 3.3. The Fundamental Variable

In Figure 7, an example of the correlation is shown. The data are from CCD0; the high pixel is at chB, and the corresponding pixel in chD is checked. A linear correlation is apparent.

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$^7$ We do not distinguish cosmic rays and hot pixels and simply call them “cosmic rays.”

$^8$ See http://www.mastars.nao.ac.jp/.

$^9$ See http://smoka.nao.ac.jp/.

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### Table 2

**Estimated Gain of SIG and PREAMP Relative to chB of CCD5**

| DET-ID | chA | chB | chC | chD |
|--------|-----|-----|-----|-----|
| 0      | 0.949 | 0.993 | 0.976 | 0.996 |
| 1      | 0.973 | 0.984 | 0.966 | 0.977 |
| 2      | 1.008 | 0.989 | 0.970 | 0.976 |
| 3      | 0.961 | 0.966 | 1.008 | 0.967 |
| 4      | 0.967 | 0.984 | 0.998 | 1.000 |
| 5      | 0.989 | 1    | 1.034 | 1.030 |
| 6      | 0.957 | 1.019 | 0.952 | 0.979 |
| 7      | 0.974 | 1.015 | 0.967 | 0.962 |
| 8      | 0.972 | 0.932 | 0.999 | 0.963 |
| 9      | 0.987 | 0.895 | 0.986 | 1.012 |
result shows that the shadow appears even in the dark data with negligible (<1 ADU) background charges. This suggests that the crosstalk phenomenon in Suprime-Cam should be a slight shift of the zero level. This assumption is consistent with the result from Giavalisco (2004a) that the effect is additive and not multiplicative. We can therefore expect that an additive correction established with these negligible background data is also valid for the object images with sky backgrounds.

We then multiply two kinds of relative gain with $v_1$. One is the value multiplied by the SIG+preamp gain in Table 2. It represents the voltage between the output of the on-chip amp and the input of SIG. We call it $v_2$. The other is the value multiplied by the total gain in Table 1, which is proportional to the photocharges. We call it $v_3$. The question is which is the fundamental variable: $v_1$, $v_2$ or $v_3$. As the gains are different among channels, the behavior of the three variables is different. A clue is the $\sim 14\%$ change in gain of the on-chip amp of chA of CCD9 in 2010 October. If crosstalk depends on photocharges ($v_3$), the coefficient of the crosstalk should change if the gain of the on-chip amp ($g_3$) changes. If crosstalk does not depend on the gain, the coefficient should remain the same.

We calculated the regression line using the data before the change in gain and tested whether the data after the change follow the same regression line. For the regression, we estimated the distribution of $v$ (other), especially the fraction of outliers. The distribution of pixel values which are not affected by the high count pixels is well approximated by a Gaussian in which $/C05< v <5/C07$, with several ($\sim 1:1 \times 10^{-4}$) outliers on the positive side. The fraction is much larger than the expected fraction of $\leq 5\sigma$ in the Gaussian $(5.7 \times 10^{-5})$ and is possibly due to weak radiation events. If we exclude $\geq 5\sigma$ data in the normal distribution, the expected reduced $\chi^2$ is only $1.5 \times 10^{-5}$ smaller. Therefore, we neglect the effect of the truncation as $\chi \leq 5\sigma$.

We restricted the data so that the input of the high count pixel is in chD and the output is in chA in order to exclude the effect of the difference in the coefficients of the different channel combinations discussed in the next section. We adopted chD because it, by chance, has more high count pixels than chB or

| EXP-ID range                     | Number of exposures | DATE-OBS   | EXPTIME (s) |
|----------------------------------|---------------------|------------|-------------|
| SUPA010806{4,8,9}                | 4                   | 2009 Mar 27| 200.0       |
| SUPA01085760                     | 1                   | 2009 Mar 30| 120.0       |
| SUPA010886{2-7}                  | 6                   | 2009 Apr 01| 300.0       |
| SUPA011221{5-7}                  | 3                   | 2009 Aug 24| 180.0       |
| SUPA012194{0-2}                  | 3                   | 2010 Apr 19| 240.0       |
| SUPA012921{2-9}                  | 8                   | 2011 Mar 06| 300.0       |
| SUPA01331150-SUPA01331260        | 12                  | 2011 Jun 03| 300.0       |
| Total                            | 37                  |            |             |

Fig. 6.—Example of a parallel overscan. The dots are the parallel overscan of a frame (SUPA01181490) after the serial overscan subtraction. The data in four channels are plotted. The solid lines are the median of the parallel overscan function of four channels of 10 CCDs of 10 exposures. The prescan region (8 pixels at the left side) is discarded. The overscan region is 48 pixels at the right side.

Fig. 7.—Example of crosstalk correlation. The high count pixel value at chB of CCD0 vs. the pixel value at chD is plotted. All of the exposures are used. The best-fit regression to the data are shown as the solid line.
chC in our data. From a likelihood-ratio test with the critical value of 5%, we obtained the result that the regression of $v_1$ and $v_2$ is not significantly different, while the regression of $v_3$ changes significantly after the change in the gain.

As another check, we plotted in Figure 8 the histogram of $a = v_{\text{other}}/v_{\text{high}}$ for $v_1$ and $v_3$ where $v_{\text{high}}$ is greater than 15,000 ADU. We can see a shift of the histogram of $v_3$, while $v_1$ remains the same. We therefore conclude that the crosstalk affects $v_1$ or $v_2$, and not $v_3$. The result resembles the result of Freyhammer et al. (2001), who noted that “Changing the gain, e.g., from low to high gain, does not alter the cross-talk amplitudes, when the cross-talk originates from the CCD itself rather than from the ADCs electronic circuits.”

The result implies that the crosstalk does not occur inside the CCD but downstream of the output of the on-chip amp. In the following analyses, we do not use $v_3$. Whether or not $v_2$ is more fundamental than $v_1$ cannot be distinguished by this CCD9 gain analysis. As the difference between $v_1$ and $v_2$ is at most 7%, as listed in Table 2, the correction of the crosstalk may have a comparable error if the wrong variable is used.

3.4. Variation of Crosstalk Coefficients

We investigated the linear correlation of each CCD for each combination of the channels because we noticed that some combination of channels have weaker crosstalk signal than others. For example, chC, affected by chB in CCD0, shows a weak crosstalk signal, as shown in Figures 9 and 10.

Ideally, we can estimate all combinations separately by investigating all possible datasets. In our data, however, some combinations do not have enough data at large $v_{\text{high}}$ and the error in the estimation of the coefficient is large. We therefore set a working hypothesis and test its validity. The hypothesis is that the coefficient is the same for the same combination in a mirror symmetry. For simplicity, we will call the data where a high count pixel is in chX and the output is chY as a crosstalk of XY and write it as cXY. From the assumption of mirror symmetry, the combinations are reduced to four groups: four of cAB-like combinations, which include cAB, cBA, cCD, cDC; four of cAC-like ones; two of cAD-like ones; and two of cBC-like ones. We call the groups gAB, gAC, gAD, and gBC, respectively. As the small $v_{\text{high}}$ data only add to the noise, we restricted the fitting range to $v_{\text{high}} > 5000$. We also tested $v_{\text{high}} > 15,000$, but the difference between them is small. The coefficients of the best-fit regressions are shown in Tables 4 and 5. The 95% confidence intervals are calculated from a likelihood-ratio test. The regression of gAB and gAC have an overlap in the confidence intervals, while the other two do not have the overlap.

Then, the data of each channel pair are compared with the best-fit function by a likelihood-ratio test with the critical value of 5%. One cBC data set (CCD5) is significantly different from the best-fit function both in $v_1$ and $v_2$. As the total number of combinations is 120, the expected number of significantly
different pairs should follow the binomial distribution Bi (120,0.05) in an ideal case. We therefore conclude that the coefficients of the crosstalk are not significantly different in the same symmetry group, and we mix all the chips and combinations in the same symmetry group hereafter. In the future, this hypothesis should be re-examined when more data are available.

As the coefficient of gBC in the same CCD is different from the other three, we can assume that crosstalk may occur around the output of the on-chip amp because the difference of gBC from the other three groups exists only inside the CCD package. This implies that \( v_2 \) would be the fundamental variable. We therefore use \( v_2 \) hereafter.

3.5. Profile Along \( x \)-Axis

We checked whether the crosstalk occurs only in the pixel corresponding to the high count pixel. If the crosstalk has a time duration, not only the pixels which were read at the same time, but also the pixels which were read later, might be affected. For example, if \((x, y)\) in chA has a high count, \([1024 - (x + \Delta x), y]\) is examined in chB, as well as the corresponding pixels in chC and chD. We should be careful in the analysis that if \([ (x + \Delta x), y] \) in chA is also a high count pixel, the shadow at \([1024 - (x + \Delta x), y]\) would be caused by a normal crosstalk effect from \([ (x + \Delta x), y]\). We therefore set an additional constraint that \([ (x + \Delta x), y]\) and the corresponding pixels in the other three channels should not be high count pixels, i.e., \( v < 300 \). We then found a sign that the confidence intervals of the coefficient are significantly different from 0 at \( \Delta x > 0 \).

For a detailed study, we select the high count pixels which extend only one pixel along the \( x \)-axis and calculate the profile of the crosstalk coefficients along the \( x \)-axis. The result is shown in Figure 11, and the coefficients around \( x = 0 \) are given in Table 6. The errorbars represent the 95% confidence intervals. The readout sequence is toward \( +x \). For example, the pixel at \( \Delta x = 1 \) is read out just after the high count pixel is read out. The profile of gAB, gAC, and gAD resemble one another. In the \( \Delta x < 0 \) region, the coefficient is \( -a \). At \( \Delta x = 0 \), the coefficient is significantly negative. It is the shadow of the crosstalk in Figure 1. Then the coefficient is back to almost 0 at \( x = 1 \), and significantly positive at \( x = 2 \). It resembles a damped oscillation pattern. On the other hand, the profile of gBC shows no significant crosstalk except at \( x = 0 \).

3.6. Crosstalk Across the CCDs

If the crosstalk occurs around the SIG, crosstalk of CCD \((2n)\) and CCD \((2n + 1)\) may occur, as they are handled in the same SIG board. This possibility is examined in the same way as in the previous section. We pick a high count pixel and check the corresponding pixels which are read at the same time in other CCDs. None of the coefficients of crosstalk across the CCDs are significantly different from 0. If we use all of the combinations, the coefficient is \(-0.01 \times 10^{-4}\), and their 95% confidence interval is \(-0.11 \times 10^{-4} < a < 0.08 \times 10^{-4}\). The result supports the assumption that the crosstalk would occur around the on-chip amp. And, the possible small crosstalk across the CCDs is negligible because the crosstalk effect is buried in the quantization noise if the coefficient is smaller than \(~1.5 \times 10^{-5}\) as discussed in § 3.1.

4. CORRECTION OF THE CROSSTALK

4.1. Procedure

We tried to correct the two significant pixels at \( x = 0 \) and \( x = 2 \) using the coefficients in Table 6. The recipe is as follows:
We assumed that the crosstalk effect is a simple sum when several high count pixels are connected in the same channel. This assumption is not perfectly additive. The coefficient of \( g_{BC} \) is nearly zero. See the online edition of the \( \text{PASP} \) for a color version of this figure.

1. Prepare an overscan subtracted image.
2. Convert the pixel value \((v_1)\) to \( v_2 \) using the gain in Table 2.
3. Visit each pixel in the frame.
4. When visiting \((x, y)\) in chA, calculate the crosstalk effect from \((1024-x, y)\) as \( \Delta x = 0 \) and \((1024-(x+2), y)\) as \( \Delta x = +2 \) in chB. The crosstalk from chC and chD are also calculated.
5. Subtract the sum of the effect from the pixel value at \((x, y)\) in the output frame.

This procedure is based on several assumptions. First, we assumed that the effects from different pixels are additive. The coefficients we use are calculated from isolated signals. We assumed that the crosstalk effect is a simple sum when several high count pixels are connected in the \( x \)-axis. This assumption is checked later. Second, we assumed that the crosstalk from different channels is also additive. This must be verified by checking whether the crosstalk signal changes when two or more pixels have high count. For example, we should check whether or not the crosstalk in chA is doubled if chC and chD are hit by cosmic rays. In the current data, such events are too few to make a conclusion. Third, we assume that the crosstalk does not affect the pixels in the same channel. This is difficult to check, since the local change of bias level from \( \Delta x = 0 \) cannot be distinguished from a change of the gain, and the effect would be very small (~10^{-4}). The \( \Delta x = +2 \) signal might be seen in the same channel, but we cannot distinguish the crosstalk signal from the original signal, as the intrinsic profile of the cosmic rays is unknown.

We checked the first assumption, that the effects from different pixels are additive, using the crosstalk corrected images and following the recipe. The profile after the correction is shown in Figure 12. As expected, the crosstalk is corrected well for single high count pixels, and most of the coefficients are consistent with no crosstalk \((a = 0)\). However, connected high count pixels show a significant sign that pixels at \( x = 0 \) in some combination have a significant signal. This means that the crosstalk phenomenon is not perfectly additive.

Recently, Nakaya et al. (2012) reported that the preamp+SIG have a remnant signal of ~1 ADU in following pixels in four channels after a 50,000 ADU signal in a channel. It corresponds to ~2 \times 10^{-5} of the coefficient at \( x = 1 \) in our analysis. The

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**TABLE 6**

**PART OF THE VALUES USED IN FIGURE 11 IN UNITS OF 10^{-4}**

| \( \Delta x \) | \( a \)  | \( a_{mn} \) | \( a_{max} \) | \( a \)  | \( a_{mn} \) | \( a_{max} \) | \( a \)  | \( a_{mn} \) | \( a_{max} \) | \( a \)  | \( a_{mn} \) | \( a_{max} \) | \( a \)  | \( a_{mn} \) | \( a_{max} \) |
|----------------|-------|---------|---------|-------|---------|---------|-------|---------|---------|-------|---------|---------|-------|---------|---------|
| −1 ......     | 0.12  | −0.43   | 0.67    | 0.08  | −0.42   | 0.57    | 0.01  | −0.56   | 0.59    | 0.15  | −0.65   | 0.96    |
| 0 ......      | −1.48 | −1.83   | −1.13  | −1.62 | −2.00   | −1.16   | −1.67 | −2.00   | −1.28   | −0.77 | −1.57   | −0.12   |
| 1 ......      | 0.02  | −0.45   | 0.48    | 0.15  | −0.38   | 0.67    | −0.02 | −0.60   | 0.57    | 0.06  | −0.77   | 0.89    |
| 2 ......      | 0.51  | 0.13    | 0.89    | 0.50  | 0.15    | 0.84    | 0.53  | 0.18    | 0.89    | 0.32  | −0.37   | 1.00    |
| 3 ......      | 0.13  | −0.48   | 0.74    | 0.09  | −0.46   | 0.63    | 0.07  | −0.38   | 0.52    | 0.18  | −0.53   | 0.90    |

*a Values significantly different from 0, i.e., \( a_{max} < 0 \) and \( a_{min} > 0 \).
different behavior of crosstalk after connected high value pixels may be a combined effect of the crosstalk and the remnant signal. Currently, it is difficult to investigate further because of the lack of sufficient data. Detailed investigation on this point will be possible when more data are available in the future.

4.2. Application to the Data

In the previous section, we get a recipe for the crosstalk correction for data with a negligible background. In this section, we will test the correction to data with a background. We will apply the correction to two kinds of astronomical data. One
is a narrowband image with a bright star. Such data has a low background sky level, and the effect of the crosstalk is apparent in a single image. The other is a deep field taken with a broadband filter. It is difficult to recognize the crosstalk in a single image, but the coadd enhances the S/N of the shadow. Then, we will estimate the effect of the crosstalk correction quantitatively.

### 4.2.1. Narrowband Images

For the first test, we used Hα (N-A-L659) data of M83 with 720 s exposure, which were used in Koda et al. (2012). After flat-fielding, the background is typically 700–900 ADU, and the rms is 20–40 ADU in a pixel. Saturated stars cause blooming of ∼900 ADU, and the shadow will be ∼10 ADU. An example is shown in the top pane of Figure 13. Though the crosstalk signal is 0.2–0.5σ in a pixel, the corresponding shadow pattern is recognized in a single image because the blooming pattern has a width of ∼20 pixels. The result of the correction is shown in the bottom pane of Figure 13. The apparent shadow is corrected by our recipe. Figure 14 is a surface brightness profile in 2″ apertures along the x-axis of the two images. The shadow is well-corrected.

### 4.2.2. Deep Field

For the second test, we adopted a part of the z-band (W-S-Z+) data of the UV4a field. The exposure time varies from 180 to 720 s. The median of the sky level is ∼26,000 ADU. The position angle is the same for all of the exposures, and crosstalk shadows of the same parity overlap at the same position. We performed a standard reduction of Suprime-Cam. After the reduction, the shadow is not obvious in a single exposure because of the high photon noise. However, it becomes apparent after the coadd of many exposures.

We picked up an example of the shadow, as shown in the top-left pane of Figure 15, and the coadd of the data corrected with our recipe is the top-right pane. Then, we divided the data into two subgroups according to the x-position of the dithering, so that the celestial position shown in Figure 15 is affected by the crosstalk in the frames of one of the groups and not in the frames of the other group. The numbers of the frames are 68 (affected) and 86 (not affected). The results of the coadd of each group are also shown in the bottom-left and bottom-right of Figure 15. The surface brightness profile of 2″ apertures along the x-axis is shown as Figure 16. It shows that the shadow at x = 100 is corrected well by our method (open circles), and the spatial profile of the coadd of the non-affected frames (filled triangles) is recovered.

### 5. Summary

Using cosmic rays in dark frames, we evaluated the crosstalk in the new Suprime-Cam FDCCDs. The strength of the crosstalk is not affected by a change of the gain of the on-chip amps, which implies that the crosstalk occurs not inside the CCD, but downstream from the output of the on-chip amp. The crosstalk effect is well approximated by a linear correlation. The coefficient seems to be correlated with the distance between the on-chip amplifiers in the CCD, which implies that the crosstalk occurs around on-chip amps. The coefficients are not significantly different among the 10 CCDs. No crosstalk is detected among the different CCDs. We also find that the crosstalk appears not only at the corresponding pixels but also at the
We present a recipe to remedy the crosstalk effect. The recipe is applied to the real data to show that it works well.

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APPENDIX

RELATIVE GAIN ESTIMATION

The data of Suprime-Cam has the GAIN information of each channel in the FITS header. The values should be $g_1 \times g_2 \times g_3$, where $g_1$, $g_2$, and $g_3$ are the gain of the analog-to-digital converter (ADC) in the SIG at each channel, the gain of the preamp of each CCD, and the gain of the on-chip amp at each channel, respectively.

The header values, however, are known to have a large error.\(^\text{10}\) The reason was that the preamp and the SIG used for the gain measurement were not the same as the ones currently being used. In particular, a SIG board with one channel was used when the gain was measured. Therefore, the GAIN values in the header represent $k \times g_3$, where $k$ is an unknown coefficient of $k = g_1(\text{old}) \times g_2(\text{old})$. As the gain of the preamp used for the measurement was $g_2(\text{old}) = 4.19$, while the typical gain of the preamps in the camera is $g_2 = 2.57$, the factor was corrected in the FITS header values.

We can see the incorrect gain problem by multiplying flat images with the GAIN values in the FITS header at each channel. An example of CCD5 is shown in Figure 17 (left). The flat pattern is the product of the quantum efficiency (QE) of each pixel, the throughput pattern of optics, and the inverse of the total gain. We expect that the QE would be continuous at the channel boundary within a small variation. The optics pattern should be smooth. As there is a level gap between adjacent channels, it must be made by incorrect gain value ratios. Namely, it should reflect the variation of $g_3$ among the channels in the same CCD.

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\(^{10}\) See http://smoka.nao.ac.jp/help/help_SUPnewCCD.jsp.
In this study, we only require the ratio of the gains, since we expect that the crosstalk would be approximated by a linear relation, which many other cameras follow. We therefore recalibrate the gain of each channel using dome flat so that the step between CCDs and channels is minimal. As the gain of one channel (chA) of CCD9 changed in 2010 October, we need to use a set before the change and a set after the change. We adopted 18 exposures of $V$, $R$, and $I$-band taken on 2010 June 10 for the former, and 38 exposures in $V$, $R$, and $i$-band taken between 2011 March 31 and 2011 April 04 for the latter. Each frame is divided by the median of the frame for normalization. Then, the median of the normalized frames is taken for each band and each CCD. This is a normal dome flat. We then extracted regions of 128 pixels wide across the channel boundary and binned by $32 \times 32$ pixels. The left two binned pixels, $vL[1]$ and $vL[2]$, are in the left channel, and the other two pixels, $vR[3]$, $vR[4]$, are in the right channel. From $vL[1]$ and $vL[2]$, $vL[3]$ is estimated by linear extrapolation, and $vR[2]$ is estimated from $vR[3]$ and $vR[4]$. The ratio $vR[3]/vL[3]$ and $vR[2]/vL[2]$ reflect the ratio of the gains of the adjacent channels. The schematic figure is shown in Figure 18. As there are 4,177 $y$-pixels in the original flat, $2 \times 130$ of the ratios are obtained. The median of the ratio gives the ratio of the gain of the adjacent channels in the CCD, and the error is estimated from median of the absolute deviation (MAD). We found that the ratio is the same within the error (typically $\sim 0.05\%$) among different bands and in different epochs, except chA of CCD9. This result supports that this method well extracts the relative gain information, as the flat pattern due to optics differs in different bands. We therefore took the median of the ratio of gains in all the bands. Except for chA of CCD9, the two epochs are mixed to calculate the relative gain.

We then estimated the ratio of the gain between neighboring CCDs. A similar method is adopted, but we adopted a binning size of $100 \times 100$ pixels; and, ratios not only of $x$-neighbors, but also of $y$-neighbors, are calculated. The relative position and rotation of the CCDs were estimated from night sky dithered exposures. We adopted the positions and the rotations as in Table 7. As the gain ratio information is redundant, we solved the overdetermined constraints by a singular value decomposition method.

The relative gain values are given in Table 1. The normalization is such that chB of CCD5 is unity, since the standard stars are often observed in the channel. The data reflect the relative values of $g_1 \times g_2 \times g_3$. The application of the new values is shown in Figure 17 (right) as an example where the gaps disappear.

Dividing the re-calibrated relative gain ($g_1 \times g_2 \times g_3$) by the GAIN values in the FITS header ($k \times g_3$), we can obtain relative gain of SIG+preamps, $g_1 \times g_2$. The values are listed in Table 2. The normalization is also at chB of CCD5. The change of the gain of chA of CCD9 in 2010 October is thought to be due to the change of the on-chip amp, and the gain of the SIG+preamp remains the same.

### Table 7

| DET-ID | $x$ (pixel) | $y$ (pixel) | $\theta$ (rad) |
|--------|-------------|-------------|----------------|
| 0      | 3153.8      | 95.7        | -0.00215       |
| 1      | 1047.7      | 95.9        | -0.00033       |
| 2      | -1066.5     | 98.5        | -0.00015       |
| 3      | 3168.0      | -4154.4     | 0.00264        |
| 4      | 1050.1      | -4150.3     | -0.00020       |
| 5      | -1086.4     | -4158.7     | 0.00014        |
| 6      | -5310.5     | 96.7        | -0.00055       |
| 7      | -3187.3     | 97.7        | -0.00003       |
| 8      | -5346.6     | -4177.5     | 0.00273        |
| 9      | -3219.1     | -4165.6     | 0.00040        |

FIG. 17.—Improvement due to the new gain data; a $V$-band domeflat of CCD0 multiplied with gain at each channel. At left is the result with the original gain value, and at right is that with the new values (in Table 1). For comparison, the images are normalized so that the median of the image is unity, and the color scales of the two are the same.

FIG. 18.—Schematic figure of the relative gain estimation.
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