Chandra Observations of Supernova 1987A

Sangwook Park[*], David N. Burrows[*], Gordon P. Garmire[*], Richard McCray[†], Judith L. Racusin[*] and Svetozar A. Zhekov[**]

[*]*Department of Astronomy and Astrophysics, 525 Davey Lab., Pennsylvania State University, University Park, PA 16802, USA*
[†]*JILA, University of Colorado, Box 440, Boulder, CO 80309, USA*
[**]*Space Research Institute, Moskovska Strasse 6, Sofia 1000, Bulgaria*

Abstract. We have been monitoring Supernova (SN) 1987A with *Chandra X-Ray Observatory* since 1999. We present a review of previous results from our *Chandra* observations, and some preliminary results from new *Chandra* data obtained in 2006 and 2007. High resolution imaging and spectroscopic studies of SN 1987A with *Chandra* reveal that X-ray emission of SN 1987A originates from the hot gas heated by interaction of the blast wave with the ring-like dense circumstellar medium (CSM) that was produced by the massive progenitor's equatorial stellar winds before the SN explosion. The blast wave is now sweeping through dense CSM all around the inner ring, and thus SN 1987A is rapidly brightening in soft X-rays. At the age of 20 yr (as of 2007 January), X-ray luminosity of SN 1987A is $L_X \sim 2.4 \times 10^{36}$ ergs s^{-1} in the $0.5-10$ keV band. X-ray emission is described by two-component plane shock model with electron temperatures of $kT \sim 0.3$ and 2 keV. As the shock front interacts with dense CSM all around the inner ring, the X-ray remnant is now expanding at a much slower rate of $v \sim 1400$ km s^{-1} than it was until 2004 ($v \sim 6000$ km s^{-1}).

Keywords: supernova remnants; supernovae; SN 1987A; X-rays
PACS: 98.38.Mz

1. INTRODUCTION

Supernova (SN) 1987A, the nearest SN in four centuries, occurred in the Large Margellanic Cloud (LMC). The identification of a Type II SN from a blue supergiant progenitor and the detection of neutrino bursts associated with the SN indicate a core-collapse explosion of a massive star [1]. SN 1987A, providing these fundamental parameters and being located at a near distance ($d = 50$ kpc), is a unique opportunity for the study of a massive star's death and the subsequent birth of a supernova remnant (SNR) in unprecedented detail.

About 10 yr after the SN explosion, the blast wave started to interact with the "inner ring" of dense circumstellar medium (CSM) [5], which is believed to be produced by the equatorial stellar winds of the massive progenitor star. This shock-CSM interaction resulted in a dramatic brightening of SN 1987A in soft X-rays, which provides an excellent laboratory for the X-ray study of the evolution of an optically thin thermal plasma in nonequilibrium ionization (NEI) as the shock propagates through a complex density gradient of the dense CSM. As the rapidly brightening X-rays begin to illuminate the interior of the SN, metal-rich ejecta expelled from the massive star's core will begin to glow optically, allowing us to study SN nucleosynthesis yields. Then, a few decades from now, when these newly-formed elements begin to cross the reverse shock surface, we will be able to measure the distribution of these elements in more detail through their

TABLE 1. Chandra Observations of SNR 1987A

Observation ID	Date (Age)[*]	Instrument (Subarray)	Exp. (ks)	Counts
124+1387[†]	1999-10-6 (4609)	ACIS-S+HETG	116.1	690[**]
122	2000-1-17 (4711)	ACIS-S3 (None)	8.6	607
1967	2000-12-07 (5038)	ACIS-S3 (None)	98.8	9030
1044	2001-4-25 (5176)	ACIS-S3 (None)	17.8	1800
2831	2001-12-12 (5407)	ACIS-S3 (None)	49.4	6226
2832	2002-5-15 (5561)	ACIS-S3 (None)	44.3	6427
3829	2002-12-31 (5791)	ACIS-S3 (None)	49.0	9277
3830	2003-7-8 (5980)	ACIS-S3 (None)	45.3	9668
4614	2004-1-2 (6157)	ACIS-S3 (None)	46.5	11856
4615	2004-7-22 (6359)	ACIS-S3 (1/2)	48.8	17979
4640+4641+5362+5363+6099[†]	2004-8-26∼9-5 (∼6400)	ACIS-S+LETG	289.0	16557[**]
5579+6178[†]	2005-1-12 (6533)	ACIS-S3 (1/8)	48.3	24939
5580+6345[†]	2005-7-14 (6716)	ACIS-S3 (1/8)	44.1	27048
6668	2006-1-28 (6914)	ACIS-S3 (1/8)	42.3	30940
6669	2006-7-28 (7095)	ACIS-S3 (1/8)	36.4	30870
7636	2007-1-19 (7271)	ACIS-S3 (1/8)	33.5	32798

[*] Days since SN

[†] These observations were splitted by multiple sequences which were combined for the analysis.

[**] Photon statistics are from the zeroth-order data.

X-ray emission. Neutrino bursts were a strong support for a core-collapse explosion, and thus for the creation of a neutron star which should become bright in X-rays.

High resolution imaging and spectroscopic studies of SN 1987A with *Chandra X-Ray Observatory* are an ideal tool for the X-ray study of SN 1987A. We have thus been observing SN 1987A with *Chandra* since its launch in 1999, roughly twice a year, in order to monitor the earliest stages of the evolution of the X-ray remnant of SN 1987A. We here review previous results from our *Chandra* observations of SNR 1987A [2, 6, 7, 8, 9, 10, 12, 13], and present some preliminary results from the latest *Chandra* observations.

2. OBSERVATIONS

Our *Chandra* observations of SNR 1987A are listed in Table 1. As of 2007 January, we have performed a total of sixteen *Chandra* observations of SNR 1987A, including two deep gratings observations. Data reduction and analysis process have been described in the literatures [2, 6, 8, 12].

3. X-RAY IMAGES

Broadband *Chandra* ACIS images of SNR 1987A are presented in Fig. 1. We applied a subpixel resolution method [11], deconvolved images with the detector point spread function (PSF), and then smoothed. The ring-like overall morphology of the X-ray rem-
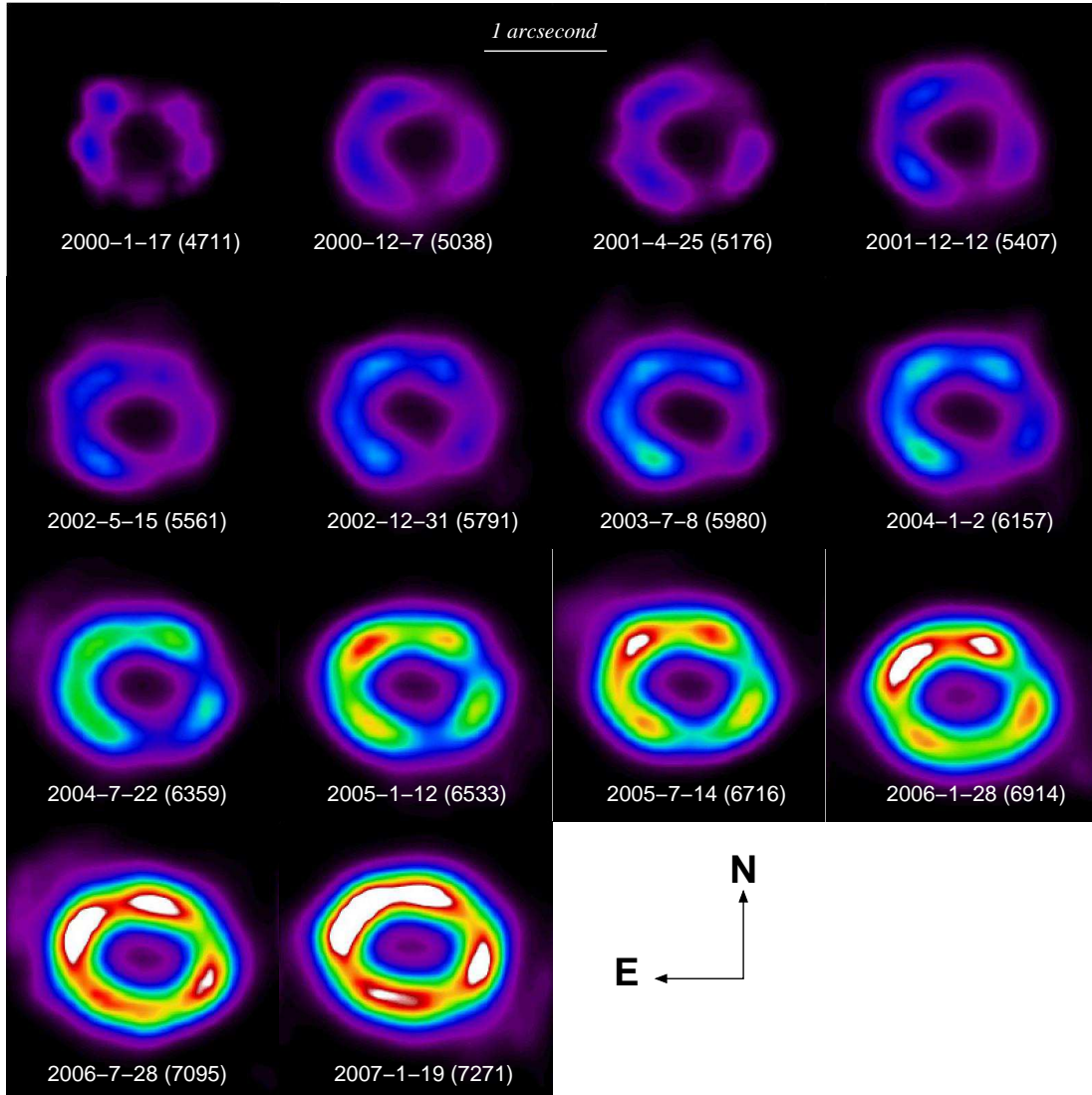
FIGURE 1. *Chandra* ACIS (in the $0.3-8$ keV band) false-color images of SNR 1987A. In each panel, the observation date and age (days since the SN, in parentheses) are presented.

nant is evident. SNR 1987A has been brightening and expanding for the last 7 yr. Initially, the eastern side was brighter, but then the western side began brightening in early 2004 (day $\sim$6200). SNR 1987A is now bright all around the ring. Early images showed that the soft X-ray band images ($E < 1.2$ keV) were correlated with the optical images while the hard band ($E > 1.2$ keV) image matched the radio images [7]. These differential X-ray morphologies supported our interpretation that soft X-rays are produced by the decelerated shock entering dense protrusions of the inner ring and that hard X-rays originate from the fast shock propagating through less dense regions between protrusions. Recent data show that the X-ray morphology is now nearly identical between the hard and soft bands, which is perhaps expected as an increasing fraction of the blast
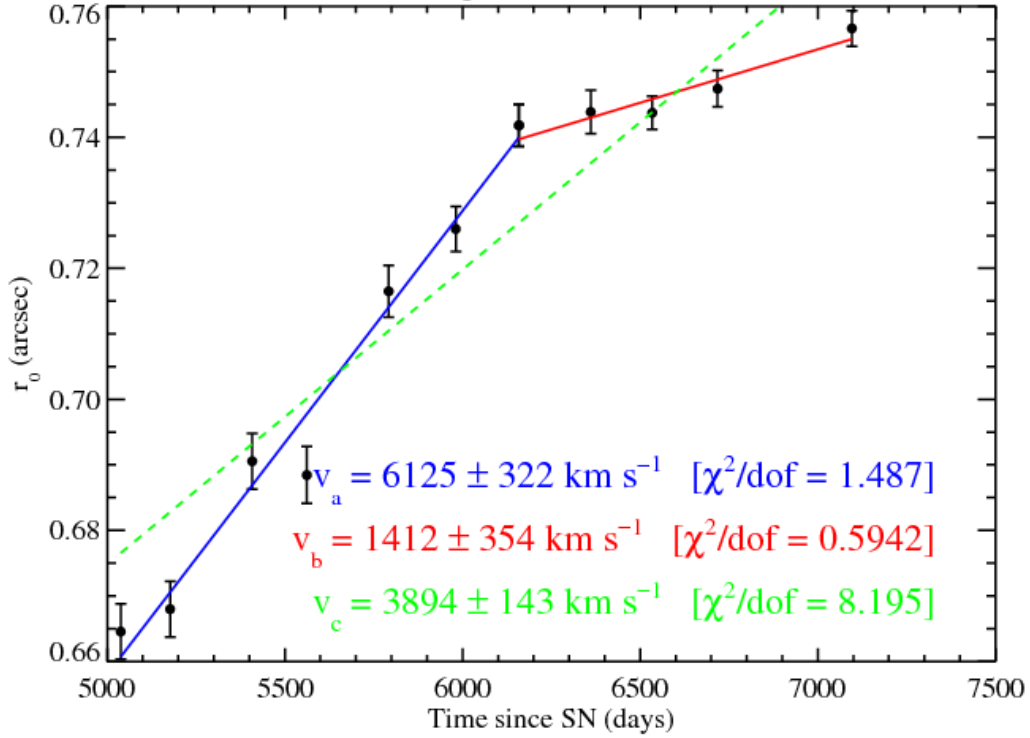
FIGURE 2. Radial expansion of SNR 1987A (taken from Racusin et al. in preparation). Data taken with the gratings are excluded. Day 4711 has also been excluded because of the low photon statistics.

wave shock front is reaching dense CSM all around the inner ring [8]. The $0.3-8$ keV band count rate is now ~ 0.98 c s^{-1}, which is ~ 14 times brighter than it was in 2000.

Assuming the apparent X-ray morphology of SNR 1987A (i.e., an elliptical torus superposed with $3-4$ bright lobes), we model X-ray images to derive the best-fit radius at each epoch. The details of our image modeling are presented in the literature (Racusin et al. in preparation). Measured radii indicate that the X-ray remnant is expanding with an overall expansion rate of $v \sim 3900$ km s^{-1} (Fig. 2), which is consistent with our previous estimates [8]. It is, however, intriguing to note that the expansion rate is significantly reduced to $v \sim 1400$ km s^{-1} since day ~ 6200 (Fig. 2). Deceleration of the expansion rate is in fact in good agreement with our interpretation of the shock reaching dense CSM all around the inner ring on days $\sim 6000-6200$ [9].

The putative neutron star has not yet become visible [2, 7, 8]. If the extinction for the SNR's center were similar to that for the entire SNR, an upper limit of $L_X(2-10$ keV$)$ $\sim 1.5 \times 10^{34}$ ergs s^{-1} has been estimated for an embedded point source [8].

4. X-RAY SPECTRUM

The X-ray spectrum of SNR 1987A is line-dominated, indicating a thermal origin (Fig. 3). As the shock interacts with increasing amount of dense CSM, multiple components of hot optically thin plasma are required to adequately fit the observed X-ray
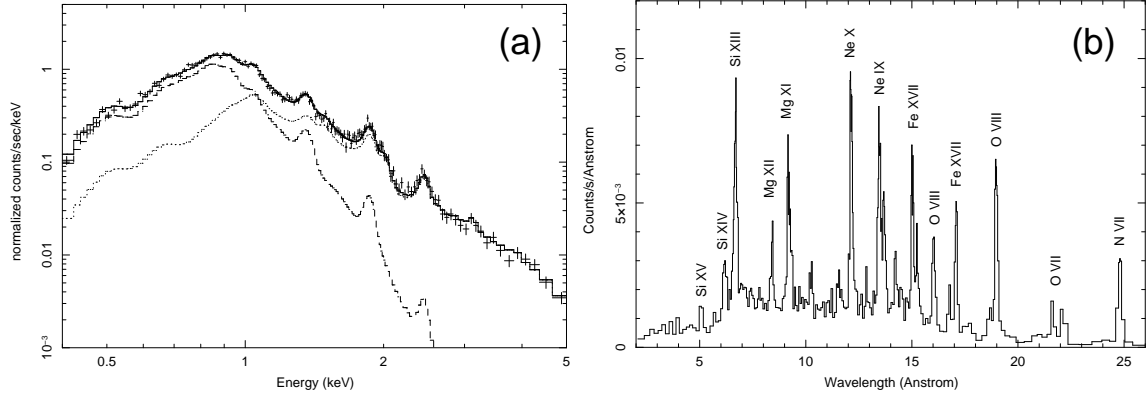
FIGURE 3. (a) The ACIS spectrum of SNR 1987A as of 2007-1-19. The best-fit two-component plane shock model is overlaid. (b) The LETG spectrum of SNR 1987A as of 2004-8 (taken from [12]).

TABLE 2. Best-Fit Parameters from the Two-Shock Model Fit of SNR 1987A

| Age* (days)	kT(soft) (keV)	kT(hard) (keV)	$n_e t$(hard) (10^{11} cm^{-3} s)	EM(soft) (10^{58} cm^{-3})	EM(hard) (10^{58} cm^{-3})	χ^2/ν
6914	$0.31^{+0.04}_{-0.02}$	$2.21^{+0.16}_{-0.07}$	$2.24^{+0.48}_{-0.40}$	$29.28^{+5.86}_{-6.75}$	$3.54^{+0.27}_{-0.21}$	178.3/142
7095	$0.29^{+0.01}_{-0.01}$	$2.03^{+0.13}_{-0.12}$	$2.63^{+0.62}_{-0.44}$	$37.89^{+1.53}_{-0.87}$	$4.65^{+0.30}_{-0.30}$	240.5/141
7271	$0.31^{+0.07}_{-0.01}$	$1.96^{+0.09}_{-0.07}$	$3.63^{+1.05}_{-0.78}$	$40.80^{+3.00}_{-13.80}$	$5.61^{+0.44}_{-0.33}$	183.6/142

* Days since SN

spectrum [8, 10, 13]. In fact, a two-temperature NEI plane shock model fits the observed ACIS spectrum of SNR 1987A (Fig. 3a). The soft and hard components characteristically represent the decelerated shock (by dense protrusions of the inner ring) and the fast shock propagating into less-dense medium, respectively. Results from two-component plane shock model fits of the ACIS spectrum for the latest three epochs, which have not been published, are presented in Table 2. The foreground column is fixed at $N_H = 2.35 \times 10^{21}$ cm^{-2} [10]. Metal abundances are fixed at values measured by Zhekov et al. [13], which are generally consistent with the LMC abundances. Ionization timescales for the soft component ($kT \sim 0.3$ keV) are high ($n_e t > 10^{12}$ cm^{-3} s), indicating the hot gas is in collisional ionization equilibrium due to the shock interaction with dense CSM.

The high resolution dispersed spectrum obtained by the deep LETG observation revealed detailed X-ray emission lines from various elemental species (Fig. 3b, [12]). The high-quality LETG spectrum showed that the continuous distribution of the shock temperature is represented by two dominant components ($kT \sim 0.5$ and 2.5 keV) [13]. The LETG spectrum indicated LMC-like metal abundances with a moderate enhancement in N [13]. X-ray line broadening measurements using the deep LETG observation indicated shock velocities of $v \sim 300-1700$ km s^{-1} [12] which are significantly lower than that deduced from the HETG observation performed $\sim$5 yr earlier ($v \sim 3400$ km s^{-1}, [6]). These results are consistent with the ACIS spectral analysis, supporting the interpretation of the blast wave recently interacting with the entire inner ring.

TABLE 3. *Chandra* Flux and Luminosity of SNR 1987A

Age[*]	$f_X(0.5-2 \text{ keV})$[†]	$f_X(3-10 \text{ keV})$[†]	$L_X(0.5-10 \text{ keV})$[**]
4711	1.61±0.66	0.84±0.57	1.54
5038	2.40±0.22	0.92±0.21	2.22
5176	2.71±0.54	1.22±0.41	2.59
5407	3.55±0.43	1.20±0.44	3.24
5561	4.19±0.46	1.49±0.64	3.79
5791	5.62±0.45	1.82±0.46	5.05
5980	6.44±0.52	1.95±0.62	5.71
6157	7.73±0.62	2.38±0.57	6.82
6359	11.48±0.69	2.40±0.60	9.54
6533	16.29±0.65	2.80±0.73	13.58
6716	19.41±0.97	3.26±0.68	16.06
6914	21.96±1.10	3.45±0.69	17.99
7095	25.56±1.28	3.84±0.77	20.58
7271	29.62±1.48	4.41±0.88	23.54

[*] Days since SN

[†] Observed flux in units of 10^{-13} ergs cm^{-2} s^{-1}

[**] In units of 10^{35} ergs s^{-1}, after corrected for $N_H = 2.35 \times 10^{21}$ cm^{-2}.
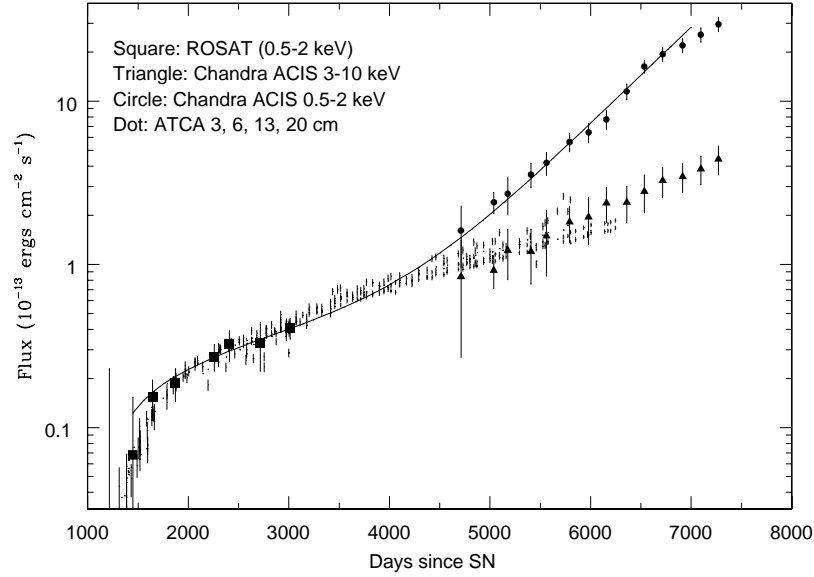
FIGURE 4. X-ray and radio light curves of SNR 1987A. Radio fluxes are arbitrarily scaled. The solid line is the best-fit model by [9]

5. X-RAY LIGHT CURVES

We present the soft ($0.5-2$ keV) and hard ($3-10$ keV) band X-ray light curves in Table 3 and Fig. 4. We also present the *ROSAT* [4] and radio[1] light curves (Fig. 4). The soft X-ray light curve has been increasing nearly exponentially for the last several yr, with apparent "upturns" on days $\sim3500-4000$ and days $\sim6000-6200$. These features were interpreted as the time when the blast wave first made contact with the dense protrusions, and the time when the shock reached the main body of the inner ring [9]. The latest data points (days $>$ 6700) suggest that the soft X-ray flux is still rapidly increasing, but probably less steeply than it was for the previous ~2 yr (Fig. 4). This latest behavior of the soft X-ray light curve might have implications for the details of the density structure of the inner ring. Periodic monitoring of the soft X-ray flux is important to study the details of the density and abundance structures of the inner ring.

The hard X-ray light curve is increasing at a lower rate than the soft X-ray light curve (Fig. 4). This slow increase rate appears to be roughly consistent with the radio light curve (Fig. 4). Hard X-rays in SNR 1987A might thus originate from the same synchrotron radiation as radio emission does. However, the morphology of hard X-ray images is no longer distinguishable from that of soft X-ray images [9]. The origin of hard X-ray emission from SNR 1987A is thus uncertain. Periodic monitoring of hard X-ray and radio light curves and searching for X-ray lines in the hard band (e.g., Fe K lines) will be important to reveal the origin of hard X-ray emission.

6. THE ACIS PHOTON PILE-UP

Based on their *XMM-Newton* data analysis, Haberl et al. [3] argued that our *Chandra* soft X-ray light curve [9] was significantly contaminated by the ACIS photon pileup. They re-estimated the $0.5-2$ keV band ACIS fluxes of SNR 1987A using archival *Chandra* data, and calculated pileup correction factors for the measured ACIS fluxes. Their $0.5-2$ keV band flux correction factors were up to $\sim25\%$, especially for recent epochs of days ~6533 and 6716. Thus, they claimed that the reported upturn of the soft X-ray light curve on days $\sim6000-6200$ [9] was an artifact caused by the photon pileup.

Haberl et al., however, misunderstood our *Chandra* instrument setup for three epochs: we used the HETG on day 4609 and a 1/8 subarray of the ACIS on days 6533 and 6716, while they assumed the bare ACIS on day 4609 and a 1/2 subarray of the ACIS on days 6533 and 6716. Their ACIS flux corrections for these epochs were thus incorrect. We note that the ACIS photon pileup is not the sole contamination, and Haberl et al. did not consider other issues such as the charge transfer inefficiency and the time-dependent quantum efficiency degradation of the ACIS data. A moderate discrepancy ($\lesssim10\%$) is also known between *XMM-Newton* and *Chandra* due to the imperfect cross-calibration between them. Furthermore, SNR 1987A is an extended source as observed with the *Chandra* ACIS, whereas a pointlike source was apparently assumed by Haberl et al.

---

[1] Radio data obtained with *Australian Telescope Compact Array* (*ATCA*) have been provided by L. Staveley-Smith.

Considering these technical issues, we have re-analyzed the possible effects of ACIS photon pile-up on our *Chandra* observations using three independent methods: PIMMS/XSPEC simulations, ACIS event grade distribution analysis, and the (*modified*) standard ACIS photon pileup model. Our results from these three analyses agree that flux correction factors due to the ACIS photon pileup are roughly several % or less, with the exception of day 6157 where ~15% of the soft X-ray flux appeared to be lost due to photon pileup (see Park et al. [in preparation] for the detailed results). Based on these results, we confirm that the scientific conclusions by Park et al. [9] were not affected by the ACIS photon pileup.

ACKNOWLEDGMENTS

REFERENCES

1. W. D. Arnett, J. N. Bahcall, R. P. Kirshner, and S. E. Woosley, *Annual Review of Astronomy and Astrophysics* **27**, 629–700 (1989).
2. D. N. Burrows, E. Michael, U. Hwang, R. McCray, R. A. Chevalier, R. Petre, G. P. Garmire, S. S. Holt, and J. A. Nousek, *The Astrophysical Journal* **543**, L149–L152 (2000).
3. F. Haberl, U. Geppert, B. Aschenbach, and G. Hasinger, *Astronomy & Astrophysics* **460**, 811–819 (2006).
4. G. Hasinger, B. Aschenbach, and J. Trümper, *Astronomy & Astrophysics* **312**, L9–L12 (1996).
5. E. Michael, R. McCray, C. S. J. Pun, P. Garnavich, P. Challis, R. P. Kirshner, J. Raymond, K. J. Borkowski, R. A. Chevalier, A. V. Filippenko, C. Fransson, P. Lundqvist, N. Panagia, M. M. Phillips, G. Sonneborn, N. B. Suntzeff, L. Wang, and C. J. Wheeler *The Astrophysical Journal* **542**, L53–L56 (2000).
6. E. Michael, S. A. Zhekov, R. McCray, U. Hwang, D. N. Burrows, S. Park, G. P. Garmire, S. S. Holt, and G. Hasinger *The Astrophysical Journal* **574**, 166–178 (2002).
7. S. Park, D. N. Burrows, G. P. Garmire, J. A. Nousek, R. McCray, E. Michael, and S. A. Zhekov *The Astrophysical Journal* **567**, 314–322 (2002).
8. S. Park, S. A. Zhekov, D. N. Burrows, G. P. Garmire, and R. McCray, *The Astrophysical Journal* **610**, 275–284 (2004).
9. S. Park, S. A. Zhekov, D. N. Burrows, and R. McCray, *The Astrophysical Journal* **634**, L73–L76 (2005).
10. S. Park, S. A. Zhekov, D. N. Burrows, G. P. Garmire, J. L. Racusin, and R. McCray, *The Astrophysical Journal* **646**, 1001–1008 (2006).
11. H. Tsunemi, K. Mori, E. Miyata, C. Baluta, D. N. Burrows, G. P. Garmire, and G. Chartas, *The Astrophysical Journal* **554**, 496–504 (2001)
12. S. A. Zhekov, R. McCray, K. J. Borkowski, D. N. Burrows, and S. Park, *The Astrophysical Journal* **628**, L127–L130 (2005).
13. S. A. Zhekov, R. McCray, K. J. Borkowski, D. N. Burrows, and S. Park, *The Astrophysical Journal* **645**, 293–302 (2006).