CHANDRA OBSERVATIONS OF SNR 1987A

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ABSTRACT

We report on the results of our monitoring program of the X-ray remnant of supernova 1987A with the Chandra X-Ray Observatory. We have performed two new observations during the Chandra Cycle 3 period, bringing the total to six monitoring observations over the past three years. These six observations provide a detailed time history of the birth of a new supernova remnant in X-rays. The high angular resolution images indicate that soft X-ray bright knots are associated with the optical spots, while hard X-ray features are better correlated with radio images. We interpret this in terms of a model in which fast shocks propagating through the circumstellar HII region produce the hard X-ray and radio emission, while the soft X-ray and optical emission arise in slower shocks entering into dense knots in the circumstellar inner ring. New observations begin to show changes in the morphology that may herald a new stage in the development of this incipient supernova remnant. The observed X-ray fluxes increase by nearly a factor of three over the last 30 months. The X-ray remnant is expanding at a velocity of \( \sim 5000 \text{ km s}^{-1} \).

INTRODUCTION

With a known age, distance, and the progenitor type, supernova (SN) 1987A provides an unprecedented opportunity for the study of the early evolution of a supernova remnant (SNR). The optical inner ring, as observed by the Hubble Space Telescope (HST) is believed to be the dense circumstellar medium (CSM) produced by the stellar winds from the massive progenitor (Luo and McCray, 1991). Inside of this inner ring is an HII region generated by the UV radiation from the progenitor (Chevalier and Dwarkadas, 1995). The development of optically bright spots along the inner ring (Pun et al., 1997; Garnavich et al., 1997) was interpreted as emission from the radiative shock where the blast wave begins to strike inward protrusions of the dense inner ring (Michael et al., 2000). In X-rays, SN 1987A was detected with the Röntgen Satellite (ROSAT) as an unresolved source and the observed X-ray flux was linearly increasing (Hasinger et al., 1996). The high angular resolution images from the Chandra observations have revealed a shell-like structure of the X-ray remnant (Burrows et al. 2000). Monitoring observations with Chandra have shown a continuous development of the X-ray bright spots, which are in general spatially coincident with the optical and radio spots; a steady increase of the soft X-ray flux; and evidence of the radial expansion of the SNR (Park et al., 2002). The thermal X-ray spectrum was fitted with an electron temperature of \( kT \sim 2.5 \text{ keV} \). The broadening of the atomic emission lines as detected with the dispersed spectrum indicated a shock velocity of \( \sim 3400 \text{ km s}^{-1} \), which provided direct evidence for electron-ion non-equilibrium behind the shock front (Michael et al., 2002). We have recently performed two new observations with Chandra, which bring the total of monitoring observations of SNR 1987A up to six. We here report an update on the results from all six monitoring Chandra observations of SNR 1987A.
OBSERVATIONS AND DATA REDUCTION

As of May 2002, we have performed a total of six monitoring observations of SNR 1987A with the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-ray Observatory (Table 1). The description of the observations and the data reduction of the first four observations can be found in literature (Burrows et al., 2000; Park et al., 2002). We have performed two new observations on December 12, 2001 and May 15, 2002 during Chandra Cycle 3. The ACIS-S3 was used without gratings. We have processed these two observations in the same way as four previous observations: i.e., we have corrected the charge transfer inefficiency (CTI; Townsley et al., 2000) with the methods developed by Townsley et al. (2002) before further standard data screenings, the sub-pixel resolution method (Tsunemi et al., 2001) was applied, and then the image was deconvolved (Burrows et al., 2000; Park et al., 2002 and the references therein) to achieve the best-utilizable angular resolution.

X-RAY IMAGES

The broad-band Chandra/ACIS images from six monitoring observations of SNR 1987A are presented in Figure 1. The overlay contours are from HST Hα data. The observation dates of the HST data are presented in the parentheses. The X-ray remnant is shell-like, as previously reported (Burrows et al., 2000; Park et al., 2002). Although the asymmetric surface brightness between the east and the west is persistent for all six images, the developments of new X-ray spots in the western half are evident in the latest images. These developing X-ray spots are spatially correlated with the optical spots. These “simultaneous” developments of the X-ray and optical spots support that the X-ray bright spots are where the blast wave is decelerated as it approaches the dense protrusions of the inner ring. We may thus expect the emergence of a complete X-ray ring in the near future as the shock front eventually strikes the main body of the entire inner ring. Park et al. (2002) have reported energy-dependent X-ray morphologies of SNR 1987A; i.e., the soft X-ray images (0.3 – 1.2 keV) were correlated with the optical images and the hard band image (1.2 – 8.0 keV) was consistent with the radio image. Figure 2 shows the development of X-ray spots in both soft and hard bands for the past 17-month period. These images confirm the previous findings that the soft X-ray spots are generally coincident with the optical spots while the hard X-ray spots are consistent with the radio bright lobes. These correlations of X-ray features with optical and radio images are consistent with the interpretation that the X-ray emission is from slow and fast shocks propagating in the HII region toward the dense inner ring.

The combined line profile as detected with the ACIS/HETG has indicated a shock front velocity of \( \sim 3400 \text{ km s}^{-1} \) (Michael et al., 2002), which was consistent with the SNR expansion rate (\( \sim 3500 \text{ km s}^{-1} \)) as measured with the radio data (Gaensler et al., 2000) and with the blast wave velocity inferred by hydrodynamic models (Borkowski et al., 1997). We can also estimate the SNR expansion rate by directly measuring the average radius of the X-ray emission as a function of time. We fit the radial count distribution with a Gaussian and use the mean radius of the best-fit Gaussian as the radial extent of the X-ray shell. Fitting these data to a linear rate, we obtain an X-ray expansion rate of \( 4954\pm1057 \text{ km s}^{-1} \) (Figure 3).

Table 1. List of the Chandra Observations of SNR 1987A

| ObsID       | Date (Age\(^a\)) | Instrument | Exposure (ks) | Src Cts |
|-------------|------------------|------------|---------------|--------|
| 124+1387\(^b\)| 1999-10-06 (4609) | ACIS-S3+HETG | 116           | 690    |
| 122         | 2000-01-17 (4711) | ACIS-S3    | 9             | 607    |
| 1967        | 2000-12-07 (5038) | ACIS-S3    | 99            | 9031   |
| 1044        | 2001-04-25 (5176) | ACIS-S3    | 18            | 1800   |
| 2831        | 2001-12-12 (5407) | ACIS-S3    | 49            | 6226   |
| 2832        | 2002-05-15 (5561) | ACIS-S3    | 44            | 6429   |

\(^a\) Day since the SN explosion in the parentheses

\(^b\) The first observation was split into two sequences, which were combined in the analysis.
Fig. 1. Exposure-corrected deconvolved X-ray images of SNR 1987A overlaid with the HST contours.

Fig. 2. Subband images of SNR 1987A.
Fig. 3. Long-term variation of the mean radius of the X-ray count distribution. The solid line is the best-fit linear rate (4954±1057 km s\(^{-1}\)).

SPECTRUM AND LIGHTCURVE

The undispersed X-ray spectrum from SNR 1987A, as extracted from the latest observation taken on May 2002, is presented in Figure 4. The spectra from five other observations show similar features to those in Figure 4. The X-ray spectrum is thermal and shows broad emission line features for the elemental species O, Ne, Mg, Si, and S. The observed spectrum is fitted with a plane-parallel shock with an electron temperature of \(kT \sim 2.5\) keV and an ionization timescale of \(n_e t \sim 5 \times 10^{10}\) cm\(^{-3}\) s. The fitted metal abundances are typically subsolar, which is consistent with the LMC ISM (Russell and Dopita, 1992) and ring abundances (Lundqvist and Fransson, 1996). The fitted electron temperature is consistent within uncertainties for all six observations. The volume emission measure (EM) has constantly increased over the past \(\sim 30\) months as the SNR has brightened. In the bottom panels of Figure 5, we present the EM (left) and the derived soft/hard X-ray fluxes (right) for the overall spectrum between January 2000 and May 2002. We have also separately performed the spectral analysis between eastern and western halves and present the best-fit EM for each half in the upper panels of Figure 5 (because of the limited photon statistics, only the latest four observations were feasible for this spectral analysis by halves). While the overall EM has been steadily increasing, the latest data begin to show different EM evolutions between the east and the west. This is an
interesting observation and may indicate some complex density variations of the CSM along the inner ring. Follow-up observations will be necessary to verify this differential developments of $EM$ between the east and the west. We derive the $0.5 - 2.0$ keV flux from each observation (Table 2) in order to monitor the long-term variations of the soft X-ray flux. The latest lightcurves are presented in Figure 6. The X-ray fluxes in Table 2 have been corrected for the ACIS quantum efficiency (QE) degradation. For comparison, the derived soft X-ray fluxes before (triangles) and after (squares) the QE correction are presented in Figure 6b. We note that the effects of the QE degradation appear to become significant since the 2000 December observation. In Figure 6a, we present the radio flux variation, which shows a deviation from the linear increase rate since 1997 (around Day 4000). The solid lines in Figure 6b represent the linear rates fitted to the first four ACIS data points as presented in Park et al. (2002). It is evident that the ACIS rate increase has turned up and that the ACIS data can no longer be fitted with a linear rate. A quadratic increase rate for the combined ($ROSAT$ + ACIS) lightcurve cannot fit the data (the dotted curve in Figure 6b). The X-ray flux has nearly tripled for the last \( \sim 30 \) months.

![Fig. 4. X-ray spectrum of SNR 1987A as observed on 2002-05-15.](image)

**POINT SOURCE**

As of 2002 May, we still observe no direct evidence of a point source within SNR 1987A. With the photon statistics of the latest data, a 90\% upper limit of the embedded point source counts is 8\% of the total SNR counts in the $2 - 8$ keV band. This implies an observed upper limit of $\sim 5.5 \times 10^{33}$ ergs s$^{-1}$ in the $2 - 10$ keV band.
Fig. 5. Emission measure/flux variations of SNR 1987A between 2000-01 and 2002-05.

Table 2. The 0.5 – 2.0 keV Flux and Luminosity of SNR 1987A from Chandra/ACIS.

| Day   | Observed Flux (10^{-13} ergs s^{-1} cm^{-2}) | Luminosity (10^{35} ergs s^{-1}) |
|-------|---------------------------------------------|-----------------------------------|
| 4609  | 1.62±0.06                                   | 0.9                               |
| 4711  | 1.74±0.07                                   | 0.9                               |
| 5038  | 2.59±0.03                                   | 1.3                               |
| 5176  | 2.93±0.07                                   | 1.5                               |
| 5407  | 3.82±0.05                                   | 2.0                               |
| 5561  | 4.45±0.06                                   | 2.2                               |

\(^a\) Day since the SN explosion.

**SUMMARY**

Since 1999 October, we have been monitoring the X-ray remnant of SN 1987A with the high resolution Chandra/ACIS instrument. With the Chandra observations, we have resolved the shell-like morphology of SNR 1987A. For the last 30 months, SNR 1987A has brightened in X-rays by nearly a factor of 3. The intensity increase rate has turned up and we can no longer fit the long-term lightcurve with a linear rate. This is good evidence of the blast wave entering the main body of the dense inner ring. With the total
of six observations now, we detect newly developing X-ray spots. The soft X-ray spots are consistent with the optical spots while the hard X-ray spots are coincident with the radio lobes. These characteristics of the X-ray spots support the interpretation that the soft spots are the X-ray emission from the slow shock encountering dense protrusions of the inner ring and that the hard spots are emission from a fast forward shock propagating through the HII region. The emergence of new X-ray spots in the western side in addition to the eastern side indicates that the X-ray emission from SNR 1987A will be a complete ring in near future. With two new ACIS observations, we confirm the previously reported radial expansion rate of the X-ray SNR. The spectrum is fitted with a plane-parallel shock model with $kT \sim 2.5$ keV and low abundances, which is consistent with the previous results indicating X-ray emission primarily from the shocked CSM. The latest observation suggests a differential evolution of the volume emission measure between the east and the west, which might be an indication of complex density structure of the CSM along the inner ring. The current data are however insufficient to make a firm conclusion and follow-up observations should be helpful to understand this feature. We obtain a 90% upper limit on the $2 - 10$ keV band X-ray luminosity $L_X = 5.5 \times 10^{33}$ ergs s$^{-1}$ for any embedded point source.
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