Supernova Remnant 1987A at the Age of 18: An On-Going Story by Chandra

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SN/SNR 1987A *in Her Uniqueness*

- **Brightest supernova** observed by mankind since 1604 (J. Kepler)
- **Distance**: 50 kpc, in the LMC
- **Age**: 18 years and 5 months old as of July 2005

- **Type II SN**
- **Progenitor**: Blue supergiant (Sk -69 202, B3 I)
- **Neutrino burst**
  => **Core-collapse explosion**

- **Most intensively studied SN of all time:**
  - Optical/UV: HST and many ground-based
  - Radio: initial detection, turned on again in ~1990
  - X-ray: no initial detection, turned on in ~1990
  - Gamma-ray: detected decay lines from $^{56}\text{Co} \rightarrow$ decay of $^{56}\text{Ni}$, confirming explosive nucleosynthesis

- **Chandra monitoring since 1999:**
  => ADS: 922 (~1/week) refereed papers (since 1987)
  - twice a year, separated by ~6 months
  - as of 2005-07, 13 observations performed
## SNR 1987A: Chandra Observations

<table>
<thead>
<tr>
<th>Date (since SN)</th>
<th>Instruments</th>
<th>Exp. (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999-10-6 (4609)</td>
<td>ACIS-S+HETG</td>
<td>116</td>
</tr>
<tr>
<td>2000-1-17 (4711)</td>
<td>ACIS-S3</td>
<td>9</td>
</tr>
<tr>
<td>2000-12-7 (5038)</td>
<td>ACIS-S3</td>
<td>99</td>
</tr>
<tr>
<td>2001-4-25 (5176)</td>
<td>ACIS-S3</td>
<td>18</td>
</tr>
<tr>
<td>2001-12-12 (5407)</td>
<td>ACIS-S3</td>
<td>49</td>
</tr>
<tr>
<td>2002-5-15 (5561)</td>
<td>ACIS-S3</td>
<td>44</td>
</tr>
<tr>
<td>2002-12-31 (5791)</td>
<td>ACIS-S3</td>
<td>49</td>
</tr>
<tr>
<td>2003-7-8 (5980)</td>
<td>ACIS-S3</td>
<td>45</td>
</tr>
<tr>
<td>2004-1-2 (6157)</td>
<td>ACIS-S3</td>
<td>46</td>
</tr>
<tr>
<td>2004-7-22 (6359)</td>
<td>ACIS-S3</td>
<td>49</td>
</tr>
<tr>
<td>2004-8-26 (6393)</td>
<td>ACIS-S+LETG</td>
<td>289</td>
</tr>
<tr>
<td>~ 2004-9-5 (6404)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005-1-9/13 (6533)</td>
<td>ACIS-S3</td>
<td>48</td>
</tr>
<tr>
<td>2005-7-11/16 (6716)</td>
<td>ACIS-S3</td>
<td>44</td>
</tr>
<tr>
<td>2005-12 (~6870)</td>
<td>ACIS-S3</td>
<td>50</td>
</tr>
<tr>
<td>2005-6 (~7050)</td>
<td>ACIS-S3</td>
<td>40</td>
</tr>
</tbody>
</table>

### Publications:
- Michael et al. 2002, 574, 166 (Obs 1 & 3)
- Park et al. 2004, AdSpR, 33, 286 (Obs 1-6)
- Park et al. 2005, AdSpR, 35, 991 (Obs 1-9)
- Racusin et al. 2005, in preparation (X-ray radial expansion: Obs 1-13)
- Zhekov et al. 2005, in preparation (Obs 11: General results from LETG spectrum)
- Park et al. 2005, in preparation (Obs 10-13: ACIS images and spectral analysis)

### Current presentation:
A review and the latest results.
SN 1987A: the Ring System (HST)

**Tarantula Nebula**

**Supernova 1987A Rings**

Inner ring is produced by fluorescence of gas in equatorial ring, ionized by initial UV flash of SN explosion.
SN 1987A: Optical Spot in the Inner Ring

**SN1987A Ring**

Bright Knot in Supernova 1987A Ring

PRC98-08b • February 10, 1998 • ST ScI OPO
P. Garnavich (Harvard-Smithsonian Center for Astrophysics) and NASA
SNR 1987A: TIME-LAPSE MOVIE (HST)

SNR 1987A: Physical Picture

Artistic presentation of SNR 1987A (SAO/CXC)

Cf. Michael et al. 1998
SNR 1987A: Radio Images (ATCA)

Australian Telescope Compact Array

Courtesy of Bryan Gaensler & Lister Staveley-Smith
SNR 1987A: First X-ray Images

ROSAT/HRI (5" pixels)
HEASARC/SkyView


Green-Blue: ACIS
Red: HST
Contour: ATCA

1 arcsecond
SNR 1987A: ACIS Images 2000-2005

Ring-like, asymmetric intensity
Developments of X-ray spots
=> becoming a complete ring as the blast wave arrives the inner ring!
Surface brightness increase
=> Now ~12 x brighter than 2000
No point source at the center

Scheduled During Chandra AO7
~2005-12
SNR 1987A: ACIS Spectrum ("2-shock" model)

\[ N_H = 2.35 \times 10^{21} \text{ cm}^{-2} \]

Soft component:
\[ kT_s = 0.23 - 0.31 \text{ keV} \]
\[ n_e t \sim 10^{13} \text{ cm}^{-3} \text{ s} \]

Hard component:
\[ kT_h = 2.2 - 3.2 \text{ keV} \]
\[ n_e t \sim 2 \times 10^{11} \text{ cm}^{-3} \text{ s} \]

Abundances fixed at values obtained from the LETG data:

- N = 0.76
- O = 0.09
- Ne = 0.29
- Mg = 0.24
- Si = 0.28
- Si = 0.45
- Fe = 0.16
Linear increase of X-ray flux until day $\sim 3000$. Rate jump in 1997 (day $\sim 3700$): coincident with emergence of optical spots. An exponential radial density profile can fit the lightcurve over a decade. An excess became evident since $d \sim 6200$. Forward shock enters a "wall"?

Forward shock enters a "wall"?

\[
0.5-2 \text{ keV} \\
3-10 \text{ keV}
\]

\[
\text{Image: ACIS 0.5-2 keV} \\
\text{Contours: HST (Credit: Peter Challis)}
\]

\[
\text{ROSAT} \quad (\text{Hasinger et al. 1996})
\]

\[
\text{X-ray Flux} \quad (10^{-13} \text{ ergs/cm}^2/\text{s})
\]

\[
\text{X-ray (2005-7) vs. Optical (2005-4)}
\]

\[
d \sim 6200
\]

\[
r/\text{ACIS}
\]

\[
\text{brium) ses}
\]

\[
\text{day/ACIS}
\]
SNR 1987A: Soft X-Ray Intensity Ratio

2002-12 to 2000-12
(5791) (5038)

Contours: 2002-12

(0.5 – 2 keV)

2005-7 to 2002-12
(6716) (5791)

Contours: 2005-7

(0.5 – 2 keV)
SNR 1987A: Hard X-Ray Emission


Image: ACIS 3-8 keV
Contours: ATCA 9 GHz

Image: ACIS 0.4-0.5 keV
Contours: ATCA 9 GHz

Similar rates of hard X-ray and radio
=> The same origin for them?
=> Simply due to softening of X-ray spectrum?

X-ray Flux ($10^{-13}$ ergs/cm$^2$/s)

Day since SN
SNR 1987A: Soft/Hard X-Ray Images

- Image: ACIS 3-8 keV
- Contours: ATCA 9 GHz

X-ray (2005-7) vs. Optical (2005-4)
- Image: ACIS 0.4-0.5 keV
  - Contours: ATCA 9 GHz
- Image: ACIS 0.8-1.2 keV
  - Contours: HST Hα
SNR 1987A: X-ray Expansion

Racusin et al. 2005 in preparation

X-ray radius vs time.

The broadband radial distribution for each observation is fitted to a Gaussian in order to estimate the radius of the SNR as a function of time.

Estimated expansion velocity is \( \sim 3155 \text{ km/s} \). But, it is apparently decelerating since \( d \sim 6200 \).

\[
\begin{align*}
\text{v}_{\text{expansion}} &= 3155 \pm 111 \text{ km/s} \\
\text{v}_{\text{expansion}} &= 3824 \pm 190 \text{ km/s} \\
\text{v}_{\text{expansion}} &= 1559 \pm 399 \text{ km/s}
\end{align*}
\]

Eli Michael / JILA

Chandra X-ray Spectrum of SNR 1987A

Background Subtracted Counts per 0.01 keV Bin vs. Energy [keV]
Combined Line Profile

Eli Michael / JILA

Dispersed Spectrum (HETG): 1999

Line width: 2300 ± 300 km/s
(single Gaussian fit)

$V_s = 3400 \pm 700$ km/s
(consistent with radio measurements)

$\Rightarrow kT_i \sim 17$ keV

Observed $kT_e \sim 2.5$ keV

Direct evidence for incomplete electron-ion thermal equilibration behind shock!
(Zhekov et al. 2005)

Detailed X-ray lines are resolved with good stats.

Individual line widths & doppler shifts are measures for the first time.

The most reliable abundance measurements.

\[ V = 340 \sim 1700 \text{ km/s} \]
(Where \( \Delta \lambda = 2\Delta \lambda_0 \pm 2z_0(\lambda/\lambda_0)^\alpha \lambda \))

South (\( m = -1 \))
North (\( m = -1 \))
Line ratios from individual species (Heα/Lyα & G-ratio of the He-like triplets) cannot be satisfied with a single kT-nt state. 
⇒ X-ray emitting plasma is in multi-
kT, Ionization states (e.g., kT = 0.1-2 keV)

Zhekov et al. 2005
SNR 1987A: Radial Expansion

- Evidence of shock wave expansion:
  - Development of optical spots: 1997 - present
  - Development of X-ray spots: 1999 - present
  - Predicted blast wave velocity from hydrodynamical models: \(\sim 4100 \text{ km/s} \) (Borkowski et al. 1997)
  - Implied shock velocity from Doppler width of X-ray dispersed lines: \(\sim 3400 \text{ km/s} \) (Michael et al. 2002)
  - Measured expansion rate of radio images: \(\sim 3000 \text{ km/s} \) (Manchester et al. 2002)

- Measurement of the radial expansion rate of X-ray images: \(\sim 3500 \text{ km/s} \), as of 2004-7.

- Since \( d \sim 6100 \), the expansion rate appears to be reduced to \( v \sim 1560 \text{ km/s} \) (from \( \sim 3400 \text{ km/s} \)).
No, NOT Detected Yet!

=> Stellar ejecta at the center of the SNR might still be optically thick in X-rays.

• Compare the observed 3-8 keV band images before and after adding simulated point sources (with various count rates) at the center of the SNR in order to determine upper limit (90%) to point source contribution.

• Point source spectrum: $\Gamma = 1.7 - 3.0$, $N_H = 2 \times 10^{21} - 10^{24}$ cm$^{-2}$ are assumed.

• Based on the image taken on 2004-7-22, a point source upper limit is $L_X (3-10 \text{ keV}) \sim 5 \times 10^{33} - 3 \times 10^{35}$ ergs s$^{-1}$

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$N_H$ = 2 x 10$^{21}$</th>
<th>$N_H$ = 1 x 10$^{24}$</th>
<th>$N_H$ = 1 x 10$^{24}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>$L_X = 7.7 \times 10^{35}$</td>
<td>$L_X = 1.3 \times 10^{34}$</td>
<td>$L_X = 2.5 \times 10^{32}$</td>
</tr>
<tr>
<td>3.0</td>
<td>$L_X = 5.2 \times 10^{34}$</td>
<td>$L_X = 1.1 \times 10^{32}$</td>
<td>$L_X = 5.0 \times 10^{31}$</td>
</tr>
</tbody>
</table>
SNR 1987A: Summary (as of 2005-7)

- Development of X-ray (and optical) spots: result of the blast wave encountering the dense CSM produced by progenitor’s stellar winds.
- Soft X-ray flux increase rate may be described by emission from shock-heated ISM with an exponential radial distribution.
- X-ray spectral variations suggest that the fast shock front is now entering the main body of the inner ring at day ~ 6000.
- A point source upper limit: $L_x (3-10 \text{ keV}) = 5 \times 10^{33} - 3 \times 10^{35} \text{ ergs s}^{-1}$.
  =&gt; A dramatic flux increase (by ~3 orders of magnitudes) has begun.
  =&gt; Spectral & morphological changes should be watched.
  =&gt; First-ever Observation of “Birth of a Supernova Remnant & a Neutron Star!!
- Deep grating (LETG) observations (Aug 26 – Sep 5, 2004) confirms X-ray emission originating from the inner ring.
- The next monitoring observations has been approved during AO8!!
  =&gt; continue to watch shock evolution, flux increase, nonthermal synchrotron emission, and neutron star.
SNR 1987A Time-Lapse Movie:
(2000-01 to 2005-01)

To be continued...

PSU/SAO/CXC