An unprecedented view of the life and death of a blue supergiant
SN 1987A: DEATH OF A STAR PROVIDES UNIQUE OPPORTUNITY

WINDOW INTO THE PAST

• Probe CSM Structure
• Ejecta morphology/abundances linked to
  => Explosion mechanism
  => Progenitor properties
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WINDOW INTO THE PAST AND FUTURE

- Massive Star
- Supernova
- Supernova Remnant

PAST

- Probe CSM Structure
- Ejecta morphology/abundances linked to
  => Explosion mechanism
  => Progenitor properties

FUTURE

- Destruction of CSM
- Dust formation/destruction?
- Evolution of ejecta
- Shock physics
- Cosmic rays
- Effect of SN/CSM on later SNR?
- Pulsar/PWN formation?
CHANDRA ACIS MONITORING CAMPAIGN

- ~6 month intervals for 16 years = 32 epochs
- Complementary to monitoring campaigns in optical, IR, radio, submm
SN 1987A WITH CHANDRA

SPECTROSCOPY

- temperatures
- densities
- ionization timescales
- abundances
- fluxes in multiple bands
- changes in all these over time

\[ t \sim 5000 \text{ days} \]

Slow cool shock = clumps
Fast hot shock = smooth ring

Energy (keV)

Normalized counts s\(^{-1}\) keV\(^{-1}\) cm\(^{-2}\)

SN1987A Age [days]

Flux [10\(^{-13}\) erg cm\(^{-2}\) s\(^{-1}\)]


ACIS (no grating)
ACIS (w/HETG)
LETG
EPIC-pn
ATCA 9 GHz
0.5 - 8 keV
0.5 - 2 keV
3 - 8 keV

Year
SN 1987A WITH CHANDRA

SPECTROSCOPY

- temperatures
- densities
- ionization timescales
- abundances
- fluxes in multiple bands
- changes in all these over time

Lots of interesting results!

t ~ 5000 days
Slow cool shock = clumps
Fast hot shock = smooth ring

![Graph showing SN1987A data over time]
SN 1987A WITH CHANDRA

SPECTROSCOPY

- temperatures
- densities
- ionization timescales
- abundances
- fluxes in multiple bands
- changes in all these over time

Lots of interesting results!

…which I’m not going to talk about today.
SN 1987A WITH CHANDRA

**IMAGING + TIME COVERAGE**

- morphology evolution
  - asymmetries
- expansion velocities
- comparisons with other wavelengths
  - timescales ~1 year

![Images and Times](images.png)
THE PICTURE SO FAR: THE EQUATORIAL RING

- **Smooth Ring**
  - \( n \sim 10^3 \text{ cm}^{-3} \)

- **Dense Clumps**
  - \( n \sim 10^4 \text{ cm}^{-3} \)

- **HII Region**
  - \( n \sim 10^2 \text{ cm}^{-3} \)

- **Cold ejecta and dust**
THE PICTURE SO FAR: THE EQUATORIAL RING

- **Smooth Ring**
  - $n \sim 10^3 \, \text{cm}^{-3}$

- **Dense Clumps**
  - $n \sim 10^4 \, \text{cm}^{-3}$

- **HII Region**
  - $n \sim 10^2 \, \text{cm}^{-3}$

- Cold ejecta and dust

Day 6000
THE PICTURE SO FAR: THE EQUATORIAL RING

Smooth Ring
\( n \approx 10^3 \text{ cm}^{-3} \)

Dense Clumps
\( n \approx 10^4 \text{ cm}^{-3} \)

HII Region
\( n \approx 10^2 \text{ cm}^{-3} \)

Cold ejecta and dust

Day 7500
THE PICTURE SO FAR: THE EQUATORIAL RING

Smooth Ring
$\sim 10^3 \text{ cm}^{-3}$

Dense Clumps
$\sim 10^4 \text{ cm}^{-3}$

HII Region
$\sim 10^2 \text{ cm}^{-3}$

Cold ejecta and dust

Day 9500
THE PICTURE SO FAR: X-RAY EXPANSION

COLLISION WITH SMOOTH RING

new density $\sim 10^3 \text{ cm}^{-3}$

$v_{early} = 6711 \pm 787 \text{ km s}^{-1}$
$v_{late} = 1854 \pm 101 \text{ km s}^{-1}$
THE PICTURE SO FAR: THE EQUATORIAL RING

ENERGY DEPENDENT EXPANSION

\[ v_{\text{ATCA}} = 3890 \pm 50 \text{ km s}^{-1} \]
\[ v_{\text{early}} = 6784 \pm 1317 \text{ km s}^{-1} \]
\[ v_{\text{late}} = -110 \pm 313 \text{ km s}^{-1} \]
\[ v_{\text{early}} = 6726 \pm 842 \text{ km s}^{-1} \]
\[ v_{\text{late}} = 1851 \pm 105 \text{ km s}^{-1} \]
\[ v_{\text{early}} = 6823 \pm 1465 \text{ km s}^{-1} \]
\[ v_{\text{late}} = 3071 \pm 299 \text{ km s}^{-1} \]
ASYMMETRIC EVOLUTION AND END OF CLUMP INTERACTION
THE PICTURE SO FAR: X-RAY MORPHOLOGY

ASYMMETRIC EVOLUTION AND END OF CLUMP INTERACTION

Sn1987A Age [days]

Year

F_{\text{half}} / F_{\text{total}}

SN1987A Age [days]


5000 6000 7000 8000 9000 10000

0.65

0.60

0.55

0.50

0.45

0.40

0.35

EW

4608
THE PICTURE SO FAR: X-RAY MORPHOLOGY

EXITING THE RING

09/2015

(10433 days)
EXITING THE RING

09/2015
(10433 days)

NEUTRON STAR NON-DETECTION

- 2-10 keV Flux $< 6 \times 10^{-4}$ counts/s
- most likely a combination of high internal absorption + too much glow from the ring
SN 1987A: DEATH OF A STAR PROVIDES UNIQUE OPPORTUNITY

WINDOW INTO THE PAST AND FUTURE

What we have learned
• HII region
• structure of inner ring
• asymmetric SN or CSM
SN 1987A: DEATH OF A STAR PROVIDES UNIQUE OPPORTUNITY

WINDOW INTO THE PAST

Massive Star

Supernova

What we have learned
• HII region
• structure of inner ring
• asymmetric SN or CSM

What’s next?
• CSM between inner and outer rings?
  - starting to probe now
• outer rings? - 20 years
What we have learned
• X-ray heating of cold ejecta and dust
• asymmetric SN?
• radio and hard X-ray share origin
• high internal absorption and/or no neutron star
SN 1987A: DEATH OF A STAR PROVIDES UNIQUE OPPORTUNITY

WINDOW INTO THE PAST AND FUTURE

What’s next?
- destruction of ring – already started!
- shocking and evolution of ejecta - within next decade
- effect of SN/CSM on later SNR? - several decades
- pulsar/PWN formation? - any time

What we have learned
- X-ray heating of cold ejecta and dust
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WINDOW INTO THE PAST AND FUTURE
What's next?
• destruction of CSM – already started!
• shocking and evolution of ejecta - over next decade
• effect of SN/CSM on later SNR? - several decades
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WINDOW INTO THE PAST AND FUTURE

What we have learned
• X-ray heating of cold ejecta and dust
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WINDOW INTO THE PAST AND FUTURE

Massive Star  
Supernova  
Supernova Remnant

Story is only just beginning!

Chandra has been critical in telling the full story so far, and will continue to be in the future.
BONUS SLIDES
IMPACT ON ASTRONOMY COMMUNITY

ADS SEARCH RESULTS

- Refereed with 1987A in title: 1190
- Refereed with 1987A in abstract: 1939
- All publications with 1987A in abstract: 4339
- All publications with 1987A and Chandra in abstract: 115
THE PICTURE SO FAR: THE (END OF) THE EQUATORIAL RING

EXITING THE RING

Year

Flux $[10^{-13}$ erg cm$^{-2}$ s$^{-1}$]

- ACIS (no grating)
- ACIS (w/HETG)
- LETG
- EPIC-pn
- ATCA 9 GHz

0.5 - 8 keV
0.5 - 2 keV
3 - 8 keV

SN1987A Age [days]
5000 6000 7000 8000 9000 10000
THE PICTURE SO FAR: THE EQUATORIAL RING

ENERGY DEPENDENT EXPANSION

44 GHz

2 - 10 keV

$V_{early} = 6784 \pm 1317 \text{ km s}^{-1}$

$V_{late} = -110 \pm 313 \text{ km s}^{-1}$

$V_{early} = 6726 \pm 842 \text{ km s}^{-1}$

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$V_{early} = 6823 \pm 1465 \text{ km s}^{-1}$

$V_{late} = 3071 \pm 299 \text{ km s}^{-1}$

SN1987A Age [days]

0 5000 6000 7000 8000 9000 10000
THE PICTURE SO FAR: THE EQUATORIAL RING

EXITING THE RING

\[ \Delta R = 0.11'' \pm 0.02'' \]
THE PICTURE SO FAR: THE EQUATORIAL RING

EXITING THE RING

ΔR = 0.12″ ± 0.02″

ΔR = 0.11″ ± 0.02″
THE PICTURE SO FAR: X-RAY HEATING

COLLISIONAL HEATING OF DUST IN RING

Gemini T-ReCS 11.7μm
Chandra contours
age~6500 days

Bouchet+2006
THE PICTURE SO FAR: X-RAY HEATING

RADIATIVE HEATING OF EJECTA

France+2015

Ly α
Ring

Ly α
F122M
Chandra
THE PICTURE SO FAR: X-RAY MORPHOLOGY

COLLISION WITH CLUMPS AND SMOOTH RING

Chandra

HST from Fransson+2015
THE PICTURE SO FAR: THE LIGHT CURVE

END OF CLUMP INTERACTION
THE PICTURE SO FAR: THE LIGHT CURVE

END OF CLUMP INTERACTION

![Graph showing SN1987A Age vs. Year and F_{30-8.0 keV} / F_{0.5-2.0 keV} for selected years between 2000 and 2016. The graph highlights a significant change in the light curve around 7000 days (approximately 19 years).]
THE PICTURE SO FAR: THE LIGHT CURVE

END OF CLUMP INTERACTION
NEUTRON STAR NON-DETECTION

POINT SOURCE FLUX LIMITS

- Procedure
  - stack 2-10 keV images (those with sufficient counts)
  - fit model image then add point source with increasing flux until delta chi2 = 2.706 (90% limit)
  - Flux < $6 \times 10^{-4}$ counts/s in 2-10 keV
  - assuming standard gamma=1.5 power law
    - $N_H = 0.235 e22 \text{ cm}^{-2} = \Rightarrow$ observed $L_X < 3.1 e33 \text{ erg/s}$
    - $N_H = 5 e22 \text{ cm}^{-2} = \Rightarrow$ intrinsic $L_X < 1.2 e34 \text{ erg/s}$
From LETG spectrum:  
(Zhekov+ 2006) 

\[
\begin{align*}
N &= 0.76 & \text{Si} &= 0.28 \\
\text{Ne} &= 0.29 & \text{S} &= 0.45 \\
\text{Mg} &= 0.24 & \text{Fe} &= 0.16
\end{align*}
\]
• 1- or 2-component NEI thermal shock model
  – Soft component:
    • $kT \sim 0.3 \text{ keV}$
    • $n_e t > 10^{12} \text{ s/cm}^3$ (≈CIE)
  – Hard component:
    • $kT \sim 1 - 3 \text{ keV}$
    • $n_e t = 2 - 3 \times 10^{11} \text{ s/cm}^3$

• Simplification of very complex, multi-shock system
t \sim 5000 \text{ days}

**Slow cool shock**

**Fast hot shock**

**Early phase, shock interacting with protrusions**
t \sim 5700 \text{ days}
Slow cool shock
Fast hot shock
Beginning of interaction with main ring
t \sim 7800 \text{ days}

Slow cool shock

Fast hot shock

Soft component increasing faster than hard component. Much new clump material being shocked.
CHANDRA SPECTROSCOPY

$t \sim 10000$ days

- Slow cool shock
- Fast hot shock

Soft component and hard component rate of increase both slow (moving through smooth ring only)
CHANDRA SPECTROSCOPY

TEMPERATURE RATIO

Graph showing the temperature ratio $kT_{Hot}/kT_{Cool}$ as a function of SN1987A age [days] and year.
CHANDRA SPECTROSCOPY

IONIZATION AGES

![Graph showing ionization ages over time](image)
CHANDRA IMAGING AND SPECTROSCOPY MOVIE
SHOCKING AND DESTRUCTION OF CLUMPS AND RING

ORLANDO+2015 SIMULATION
X-RAY HEATING OF THE OPTICAL EJECTA

X-RAYS RADIATIVELY HEAT OUTER LAYER OF DEBRIS

Larsson+2013
OPTICAL (RE)BRIGHTENING OF RING, EJECTA EXPANDS AND FADES

Fransson+2015
EARLY MULTI-\(\lambda\) IMAGES

SOFT/ OPTICAL=CLUMPS

HARD/RADIO=HII

Park+2002