WHAT DO X-RAY OBSERVATIONS OF SNRS TELL US ABOUT THE SN AND ITS PROGENITOR

DAN PATNAUDE (SAO)
ANATOMY OF A SUPERNOVA REMNANT

Forward Shock

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
ANATOMY OF A SUPERNOVA REMNANT

Forward Shock

shock accelerated electrons mark the location of the $u_s \sim 5000 \text{ km s}^{-1}$ shock

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
Forward Shock

shock accelerated electrons mark the location of the $u_s \sim 5000$ km s$^{-1}$ shock

forward shock acts as a probe of the CSM structure and composition

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
CSM consists of a $\rho \propto r^{-2}$ wind with dense clumps with $u_w \sim 20$ km s$^{-1}$.

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.

**ANATOMY OF A SUPERNOVA REMNANT**

**Forward Shock**

**Shocked CSM**

**Shock Ejecta**

Metal rich ejecta shows elevated abundances of explosive nucleosynthesis and sometimes evidence for macroscopic mixing between mass layers.

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
Differing wavebands reveal a different evolutionary state of the SNR - X-ray emission reveals the dynamically oldest ejecta
G292.0+1.8: A MASSIVE PROGENITOR IN A DENSE WIND

$t_{SNR} \sim 1600 \text{ yr}$

$D_{SNR} \sim 4 \text{ kpc}$

shows primarily shock heated CSM - consistent with age estimate

Composite image of G292.0+1.8. (CXC/S. Park)
G292.0+1.8: A MASSIVE PROGENITOR IN A DENSE WIND

\[ t_{\text{SNR}} \sim 1600 \text{ yr} \]

\[ D_{\text{SNR}} \sim 4 \text{ kpc} \]

shows primarily shock heated CSM - consistent with age estimate

G292.0+1.8 (Lee et al., 2010)
G292.0+1.8: A MASSIVE PROGENITOR IN A DENSE WIND

t_{SNR} \sim 1600 \text{ yr}

D_{SNR} \sim 4 \text{ kpc}

G292.0+1.8 (Lee et al., 2010)
G292.0+1.8: A MASSIVE PROGENITOR IN A DENSE WIND

Authors estimate 15-40M$_{\text{sun}}$ of wind material swept up by shock

G292.0+1.8 (Lee et al., 2010)
G292.0+1.8: A MASSIVE PROGENITOR IN A DENSE WIND

Authors estimate 15-40M$_{\odot}$ of wind material swept up by shock

Estimate MS progenitor mass of ~ 25M$_{\odot}$

G292.0+1.8 (Lee et al., 2010)
EJECTA AS A PROBE OF THE CSM AROUND CAS A

emission from shocked ejecta is impacted by structure of CSM

strength of reverse shock determines how much energy is deposited in ejecta...

Broadband X-ray image of Cas A (Hwang & Laming 2009)
EJECTA AS A PROBE OF THE CSM AROUND CAS A

emission from shocked ejecta is impacted by structure of CSM

... a low density CSM produces a weak reverse shock that will not penetrate into the deeper layers of ejecta

1100 yr old SNR 1E0102.1-7219 shows emission from O, Ne, and Mg only (courtesy CXC)
EJECTA AS A PROBE OF THE CSM AROUND CAS A

ionization balance of silicon rich regions of ejecta suggests a slow wind

Spectrum from Hwang & Laming (2009)

Broadband X-ray image of Cas A (Hwang & Laming 2009)
EJECTA AS A PROBE OF THE CSM AROUND CAS A

ionization balance of silicon rich regions of ejecta suggests a slow wind

Spectrum from Hwang & Laming (2009)

Broadband X-ray image of Cas A (Hwang & Laming 2009)
EJECTA AS A PROBE OF THE CSM AROUND CAS A

ionization balance of silicon rich regions of ejecta suggests a slow wind

ratio of He-like to H-like ions indicates a 0.2 pc cavity around Cas A prior to the explosion

Broadband X-ray image of Cas A (Hwang & Laming 2009)
X-RAY EMISSION AS A PROBE OF EJECTA COMPOSITION

fitted ionization age ($n_{et}$) indicates that most X-ray bright regions were shocked $\sim 20$-200 yr ago

Region with highest ionization age corresponds to Fe-rich region - supports theory that Fe-rich plumes overturned during explosion
X-RAY EMISSION AS A PROBE OF EJECTA COMPOSITION

fitted ionization age ($n_{\text{et}}$) indicates that most X-ray bright regions were shocked ~ 20-200 yr ago

Region with highest ionization age corresponds to Fe-rich region - supports theory that Fe-rich plumes overturned during explosion

Iron abundance relative to solar in Cas A (Hwang & Laming 2012)
X-RAY EMISSION AS A PROBE OF EJECTA COMPOSITION

fitted ionization age ($n_{et}$) indicates that most X-ray bright regions were shocked ~ 20-200 yr ago

Region with highest ionization age corresponds to Fe-rich region - supports theory that Fe-rich plumes overturned during explosion

Ionization parameter vs position in Cas A (Hwang & Laming 2012)
Silicon abundance relative to solar in Cas A (Hwang & Laming 2012)

fitted ionization age ($n_{\text{e}t}$) indicates that most X-ray bright regions were shocked $\sim$ 20-200 yr ago

Region with highest ionization age corresponds to Fe-rich region - supports theory that Fe-rich plumes overturned during explosion
DISTRIBUTION OF “PURE” Fe EJECTA IN CAS A (HWANG & LAMING 2012)

Find $M_{Fe} = 0.09 - 0.13M_{sun}$

ALL Fe produced in Cas A explosion has now been shocked

$Fe_{Si} = 0.075 - 0.11 \, M_{\odot}$

$Fe_{\alpha} = 0.023 - 0.03 \, M_{\odot}$

Consistent with Cas A NS atmosphere being composed of carbon
**TEMPORAL VARIATIONS**

multiepoch observations reveal fading and brightening of thermal and nonthermal emission

rise time in X-ray emission from any particular feature is dependent upon the density of the emitting material - reveals anisotropy in expanding ejecta (Patnaude & Fesen 2007)

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
TEMPORAL VARIATIONS

multiepoch observations reveal fading and brightening of thermal and nonthermal emission

\( \chi \sim 2-4 \) between X-ray bright knots and diffuse X-ray component - “knots” are not really knots (\( \Delta \text{EM between knots and diffuse component} = 4-16 \))

Cas A viewed in X-rays (Patnaude & Fesen 2009). Red corresponds to 0.7-1.2 keV, green to 1.5-3.0 keV and blue to 4.2-6.0 keV.
TEMPORAL VARIATIONS - CAS A - EJECTA

Brightening of filament marks the location of the reverse shock.

Si-bright filament at base of NE jet in Cas A
TEMPORAL VARIATIONS - CAS A - EJECTA

Si-bright filament at base of NE jet in Cas A

Rate at which plasma reaches ionization equilibrium is related to $\rho$ and $\mathcal{E}$ - relates back to explosion energetics
\[ \frac{1}{F_X} \frac{dF_X}{dt} \sim -2\% \text{ yr}^{-1} \]

decline in nonthermal emission suggests loss of energy to efficient cosmic ray acceleration

\[ \frac{dV_s}{dt} \propto \frac{dE_c}{dt} \approx -20 \text{ km s}^{-1} \text{ yr}^{-1} \]
\[ \frac{1}{F_X} \frac{dF_X}{dt} \sim -2\% \text{ yr}^{-1} \]

The decline in nonthermal emission suggests loss of energy to efficient cosmic ray acceleration.

The location of nonthermal emission (RS vs FS) may depend on nucleosynthesis processes during explosion (e.g. Zirakashvili & Aharonian 2011).
DETECTION OF CENTRAL COMPACT OBJECTS

Some Type IIL SNe (79C, 80K, 85L could be powered by the formation of a magnetar (Kasen & Bildsten 2010; Woosley 2010):

\[ L_p = 2 \times 10^{42} B_{14}^2 (t/\text{yr})^{-2} \text{erg s}^{-1} \]

at late times, the X-ray emission from the central object might be observed

Composite image of M100 with data from Spitzer (red), VLT (blue), and Chandra (yellow) (CXC/Patnaude)
SN 1979C:

- observed with every X-ray satellite since *Einstein*
- X-ray emission has remained constant with time. Expect that:

\[ L_X \propto t^{-n} \]

\( L_x = (6.5 \pm 0.1) \times 10^{38} \text{ erg s}^{-1} \)

X-ray lightcurve of SN 1979C (Patnaude et al., 2011)
SN 1979C:

- model the X-ray emission as some fraction of magnetar spin down luminosity
- ROSAT and early CXO observations are consistent with this scenario, but quickly diverge

\[ L_X = 0.1L_p \propto t^{-2} \]

X-ray lightcurve of SN 1979C (Patnaude et al., 2011)
SN 1979C:

• In reality, X-ray emission is probably some combination of emission from shocked material and any central object.

• After an initial rise time, X-ray emission from shocked material:

\[ L_X \propto t^{-1} \]

\[ n^2 V \propto t^{-1} \]

\[ L_X = 0.1 L_p \propto t^{-2} \]

\[ E_{SN} = 2 \times 10^{51} \text{ erg} \]

\[ \dot{M} = 1.5 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \]

\[ v_{\text{wind}} = 20 \text{ km s}^{-1} \]
SN 1979C:

in ejecta:
\[ \tau \ll 1 \text{ after } \sim 10 \text{ yr} \]

model a central compact object:

Luminous Crab-like PWN with \( t_P \sim 1000 \text{ yr} \)?

X-ray lightcurve of SN 1979C (Patnaude et al., 2011)
SN 1979C:
in ejecta:
\[ \tau \ll 1 \text{ after } \sim 10 \text{ yr} \]

model a central compact object:

Luminous Crab-like PWN with \( t_p \sim 1000 \text{ yr} \)?

\[ L_X (\text{Crab}) \sim 10^{37.4} \text{ erg s}^{-1} \]

PWN in 79C would be 25x more luminous than the Crab!

X-ray lightcurve of SN 1979C (Patnaude et al., 2011)
SN 1979C:
in ejecta:  
$\tau << 1$ after $\sim 10$ yr

model a central compact object:

**BH accreting near Eddington Limit?**

---

**X-ray lightcurve of SN 1979C**  
(Patnaude et al., 2011)
SN 1979C:

in ejecta:
\[ \tau \ll 1 \text{ after } \sim 10 \text{ yr} \]

model a central compact object:

BH accreting near Eddington Limit?

\[ L_{\text{Edd}} = 1.4 \times 10^{38} \left( \frac{M_x}{M_\odot} \right) \text{ erg s}^{-1} \]

\[ \Rightarrow M_{\text{BH}} \approx 5M_\odot \]

X-ray lightcurve of SN 1979C
(Patnaude et al., 2011)
SN 1979C:

in ejecta:
\[ \tau \ll 1 \text{ after } \sim 10 \text{ yr} \]

High mass ejecta model overpredicts X-ray emission, while low mass model underpredicts the emission. The answer is probably somewhere in the middle, with a combination of emission from shocked material and a central object.
**Bulk Properties of SNR - Connections to the SNe and Progenitor**

Can use the properties of the X-ray spectrum to constrain the progenitor type and its evolution.

Analysis of SN Ia X-ray spectra compare directly to SN Ia models (Badenes et al. 2006, 2008; Patnaude et al. 2012).

Chandra ACIS-S Spectrum of Kepler's SNR
X-ray spectrum indicates a solar mass of $^{56}$Ni was synthesized, suggesting that Kepler’s SNR was a 1991T like event.

Line centroids and flux ratios suggest that the progenitor’s companion had typical AGB mass loss parameters, and a small cavity was located around the progenitor prior to the SN.
For SN Ia, bulk properties teach us about the explosion and progenitor history
Can the same techniques be used for more complicated CCSNe?

CCSNe show wealth of asymmetry and macroscopic mixing

Integrated X-ray spectra from 3 CCSNe scaled to 3.4 kpc
Can the same techniques be used for more complicated CCSNe?

CCSNe show wealth of asymmetry and macroscopic mixing.

Current studies only focus on piecewise studies of emission (e.g., Lee et al.; Hwang & Laming) to infer CSM or explosion properties.

Integrated X-ray spectra from 3 CCSNe scaled to 3.4 kpc.
Can the same techniques be used for more complicated CCSNe?

CCSNe show wealth of asymmetry and macroscopic mixing.

Simple self-similar models with composition derived from spectral fits show reasonable agreement with data (there’s hope!)

\[ \rho_{\text{ej}} \propto r^{-n} \]

Integrated silicon emission from Cas A
Can the same techniques be used for more complicated CCSNe?

CCSNe show wealth of asymmetry and macroscopic mixing.

Evolve Woosley & Heger (2007) models from ages of ~ 100 days to 1000 yrs.
Can the same techniques be used for more complicated CCSNe?

CCSNe show wealth of asymmetry and macroscopic mixing.

Evolve Woosley & Heger (2007) models from ages of ~100 days to 1000 yrs.

Include prescription for mixing as well as integrated mass loss history of progenitor.
s25D model evolved to $t_{SNR} = 2500$ yr in multiple CSM environments
qualitatively, the evolution of s25D SN ejecta models match observations of young SNR
CONCLUSIONS

• X-ray emission from swept up CSM and shocked ejecta can be used to constrain progenitor mass and mass loss history

• X-ray observations show that the bulk of Fe produced in Cas A is already shocked

• Bulk properties of CCSN progenitor models can be compared directly to X-ray observations of young SNRs