EXPLOSION AND CIRCUMSTELLAR ASYMMETRIES REVEALED IN THE CAS A SUPERNOVA REMNANT

DAN PATNAUDE (SAO)

ROB FESEN (DARTMOUTH COLLEGE), J. MARTIN LAMING (NRL), JACCO VINK (UNIVERSITY OF AMSTERDAM), DAN MILISAVLJEVIC (PURDUE UNIVERSITY), CRAIG HEINKE (UNIVERSITY OF ALBERTA), WYNN HO (HAVERFORD COLLEGE), DAN CASTRO (SAO)
A MONITORING PROGRAM OF CAS A

Only nearby SNR to show yearly variations in thermal and nonthermal emission, and also evidence for a young and evolving neutron star
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- thermal emission traces structure of ejecta and circumstellar environment
- nonthermal emission informs us on magnetic field amplification and diffusive shock acceleration
- changes in neutron star emission test models for solid state astrophysics
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\[
\begin{align*}
\frac{dV_s}{dt} & \lesssim -100 \text{ km s}^{-1} \text{ yr}^{-1} \\
\frac{dV_s}{dt} & = 3.5 \times 10^6 \left( \frac{V_s}{\text{km s}^{-1}} \right)^{-1} \eta \frac{dE_c}{dt}
\end{align*}
\]

Castro et al. in prep.
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Wijngaarden et al. (2019)
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- thermal emission traces structure of ejecta and circumstellar environment
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For each epoch from 2000 - 2018:
- pixels are selected using a Weighted Voroni Tessellation with S/N > 80 (> 1000 counts/region)
- due to the bulk expansion of Cas A, the region locations and number of regions are epoch dependent
- spectral parameters in any region are a convolution of the emission from that region and contributions from adjacent pixels
- use WVT mask to inform fitting parameters
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- use WVT mask to inform fitting parameters

\[ p_i = \frac{\sum_{i \neq j} \left( p_j w_{ij} \sigma_j^{-2} \right)}{\sum_{i \neq j} \left( w_{ij} \sigma_j^{-2} \right)} \]

Schematic representation of how adjacent regions contribute to the initial spectral parameter estimates for the region in yellow
Fits to each region produce a distribution of temperatures, ionization states, and chemical compositions.

Comparisons of the distribution of fit parameters from different cardinal directions highlight asymmetry in the SNR.
In each region, abundances are fit relative to oxygen.
- Fe/Si is generally higher in east than in north (~0.5).
- Results are broadly consistent with Laming & Hwang (2003) and $15M_{\odot}$ progenitor models.

Beyond larger scatter in 2018 dataset, no gross differences are seen in the abundances between 2000 and 2018.
**Quantitative Differences Between Regions**

<table>
<thead>
<tr>
<th></th>
<th>$T_e$ (keV)</th>
<th>$n_{e,\text{t}}$ ($10^{11} \text{ s cm}^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>2018</td>
<td>1.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- “k-means” test computes cluster averages from 2D distribution
- Outliers can drag mean away from “best fit (by eye)”
- Underlying kernel is dependent upon the explosion, composition, and circumstellar properties
- Differences between epochs also reflect underlying adiabatic expansion of the SNR (Sato et al. 2017)
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<tr>
<td>2000</td>
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<td>2018</td>
<td>1.9</td>
<td>1.6</td>
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- North region probably consists of more than one cluster

Spectral fit clustering for north (2018)
QUANTITATIVE DIFFERENCES BETWEEN REGIONS

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<tr>
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- West region shows highest ionization ages
- In all, results are broadly consistent with results from Hwang and Laming
- Changes in $T_e$ and $n_e t$ can be compared against 3D models
COMPARISONS TO 1D HYDRO MODELS

Model Cas A evolution to compare against the observed properties of the ejecta

\[ \rho_{\text{CSM}} = \frac{\dot{M}}{4\pi v_w r^2} \]

\[ v_w = 15 \text{ km s}^{-1} \]

\[ M_{\text{dot}} = 2 \times 10^{-5} M_{\odot} \text{ yr}^{-1} \]

Use chemical composition from a model for SN 1993J, mapped onto a self-similar ejecta profile

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

\[ M_{\text{ej}} \approx 3 M_{\odot} \]

\[ E_{\text{SN}} = 1.5 \times 10^{51} \text{ erg} \]
**Comparisons to 1D Hydro Models**

Model Cas A evolution to compare against the observed properties of the ejecta.

- Ionization state and temperature of the ejecta are inconsistent with pure \( r^{-2} \) winds.

Use chemical composition from a model for SN 1993J, mapped onto a self-similar ejecta profile.

- \( \rho_{e,j} \propto v^{-n} \)
- \( M_{e,j} \approx 3 \, M_\odot \)
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\rho_{\text{CSM}} = \frac{\dot{M}}{4\pi v_w r^2} \right\}
\begin{align*}
v_w &= 15 \text{ km s}^{-1} \ (r > 0.2 \text{ pc}) \\
v_w &= 10^3 \text{ km s}^{-1} \ (r < 0.2 \text{ pc}) \\
M_{\text{dot}} &= 2 \times 10^{-5} \ M_{\odot} \text{ yr}^{-1}
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CSM models which include a small cavity produce larger SNR at 340 years, and generally lower ionization ages in the shocked ejecta.

Possible CSM for Cas A progenitor
COMPARISONS TO 1D HYDRO MODELS

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Origin of the cavity could be from:

i: binary interaction

ii: enhanced, late stage mass loss

CSM production generally in ejecta
- cavities around IIb and Ib/c SNe appear to be common
- an increase in X-ray emission signals the interaction between the shock and denser circumstellar material

\[ L_X = \left( \frac{4}{\pi \dot{m}^2} \right) \left( \frac{\dot{M}}{v_w} \right) \frac{\Lambda(T)}{R_s} \]

data from: Dwarkadas & Gruszko (2012); Margutti et al. (2017); Kundu et al. (2019); Patnaude et al. (2019, in prep); Milisavljevic & Fesen (2008); Lee et al. (2014); Xi et al. (2019)

CSM properties for several Ib/c and IIb SNe and SNR

\[ v_{\text{wind}} = 10^3 \text{ km s}^{-1} \]

\[ v_{\text{wind}} = 10 \text{ km s}^{-1} \]
Comparisons to 1D Hydro Models

1D models also inform us on large scale azimuthal asymmetries in the ejecta

- In broad terms, different cardinal directions favor different ejecta power law indices

\[ E_{SN} \propto M_{ej}^{5/7} \frac{(n - 3)^{5/3}}{n^{2/3}(n - 5)} \]

- When ejecta mass and ejecta core density are held constant, lower values of “n” correspond to higher explosion energies
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20 Years of Chandra

Dan Patnaude (SAO)
AZIMUTHAL DIFFERENCES IN SPECTRAL FITS

- Spectral fits in the east regions point to lower ejecta densities
  - observed lower densities suggest $^{56}$Ni heating of ejecta plume
  - radioactive heating can alter ejecta structure and force a different time evolution of the density
- west region shows highest ionization —> Fraschetti et al. argued that this is due to interaction w/ a molecular cloud
- Zhou et al. showed that cloud is not coincident with Cas A
- optical observations suggest a larger concentration of CSM in that direction (QSFs) which would lead to multiple reflected shocks in the ejecta, raising the ionization age
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- Spectral fits in the east regions point to lower ejecta densities.
- Observed lower densities suggest $^{56}$Ni heating of the ejecta plume.
- Radioactive heating can alter the ejecta structure and force a different time evolution of the west region.
- Zhou et al. showed that the cloud is not coincident with Cas A.
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Wongwathanaratt et al. (2017)
AZIMUTHAL DIFFERENCES

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- Observed lower densities suggest heating of the ejecta plume with radioactive heating, which can alter the ejecta structure and force a different time evolution of the density.
- The west region shows the highest ionization, which Fraschetti et al. argued is due to interaction with a molecular cloud.
- Zhou et al. showed that the cloud is not coincident with Cas A.
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Li, McCray, and Sunyaev (1993)

\[ \tau \gg 1 \text{ ejecta} \]

\[ f = 0.2 \]
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$n = 12$ hydro models

Spectral fit clustering for west (2018)

- no cavity
- $r = 0.1$ pc
- $r = 0.2$ pc
- $r = 0.3$ pc

log$_{10}[\tau/(\text{cm}^{-3} \text{ s})]$ vs. log$_{10}[T_e/(\text{K})]$
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• optical/NIR observations suggest a larger concentration of CSM in that direction (QSFs; Koo et al. 2017) which would lead to multiple reflected shocks in the ejecta, raising the ionization age
CONCLUSIONS

• X-ray observations of thermal emission from SNR inform us on the properties of both the circumstellar environment and explosion

• Cas A shows azimuthal variations in the bulk spectral properties of the ejecta — can be explained by $^{56}\text{Ni}$ heating of ejecta in the east and (possibly) the north

• Spectral features (ionization age, line centroids) suggest a late stage enhanced mass loss event in Cas A, possibly due to a short YSG phase or binary interaction
WHAT COULD BE DONE IN THE NEXT 20 YRS?

- Uncover any unshocked iron — reconcile with models for explosive nucleosynthesis, mixing, etc.,

- Measure the blastwave deceleration — combined with measurements of synchrotron emission changes, provides a direct measurement of the CR diffusion parameter

- Determine the nature of the nonthermal emission located in the main shell — is it from the reverse shock or forward shock seen in projection?

- Settle the question of the cooling CCO — is it real or a detector artifact?