SN Ia Progenitor Signatures in Supernova Remnant Abundances

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Abundance determination in SNRs as a tool to study SN explosions:

What is in here? \(\Rightarrow\) Easy

How much of X? \(\Rightarrow\) Requires modeling

- Many open issues in Type Ia SNe require yields (explosion mechanism).

- Bulk yields (as they can be measured now) do not shed much light onto the progenitor problem!

- SNRs are nearby \(\Rightarrow\) can be studied in great detail.
SNRs: A New Window Onto SN Explosions

- *Chandra* and *XMM-Newton* provide excellent data sets [Badenes 10, PNAS 107, 7141].

- No longer a single line of sight into a distant object! ⇒ Detailed view of the ejecta structure and the immediate surroundings (CSM, stellar populations).

- We KNOW the environment affects SN Ia explosions [Howell, Mannucci talks].

- If we can connect SNRs to their SNe, we can hope for progress...

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**Warren et al. 05, ApJ 634, 376**

**Tycho SNR**

Fe L Si K 4-6 keV
Nonequilibrium Ionization in SNRs

The plasma in SNRs is in nonequilibrium ionization (NEI) ⇒
The X-ray spectrum is tied to the hydrodynamics

[talk by Jacco Vink]

Two approaches:

- **Simplify the hydro** (e.g., plane shock models [Hughes et al. 00, ApJ 543, L61; Borkowski et al. 01, ApJ 548, 820]) ⇒ Relative abundances, $n_e$, $T_e$ ⇒ Study local plasma. ⇔ SYNOW

- **Full-fledged HD+NEI** [Hamilton & Sarazin 84 ApJ 287, 282; Badenes et al. 03 ApJ 593, 358; Sorokina et al. 04, Ast. Lett 30, 737] ⇒ Bulk yields ⇒ Compare to SN physics (so far, 1D!). ⇔ Rad. Transfer
Type Ia SNRs: Tycho

The X-ray spectra from Type Ia SNRs can be used to estimate peak the brightness of SN Ia


- Type Ia SN brightness estimate based on 1D DDT models \( \Leftrightarrow M_{56Ni} \). These models work very well [Gal-yam talk]!

- Tycho SNR: \( M_{56Ni} = 0.74 \, M_\odot \) [Badenes et al. 06, ApJ 645, 1373], a normal SN Ia.

- This result was later confirmed by light echo spectroscopy [Rest et al. 08, ApJ 681, L81; Krause et al. 08, Nat 456, 617].
Age is known (SN1572). SNR size forces a correlation between D and ρ_{AM}.

- Only 1D DDT models can reproduce both X-ray spectrum and SNR dynamics.
- Crucial sanity check on yields.
- **Warning:** comparison of models and observations is not trivial!
Type Ia SNRs: Tycho

SN 1994D in NGC 4526 (P. Challis)

Best DDT
DDTc ($\rho_{AM}=2e-24$, $\beta=0.03$); $N_H=0.55$

Best 3D Deflagration
b30_3d_768 ($\rho_{AM}=2e-25$, $\beta=0.01$); $N_H=2.33$

Best sub-Chandrasekhar
SCH ($\rho_{AM}=5e-25$, $\beta=0.01$); $N_H=1.03$

Best 1D Deflagration
W7 ($\rho_{AM}=5e-25$, $\beta=0.1$); $N_H=1.07$
Type Ia SNRs: SNR 0509-67.5

- **SNR 0509-67.5** in the LMC ⇒ $M_{56Ni} = 0.97 \, M_\odot$ [Badenes et al. 08, ApJ 680, 1149].

Also confirmed by the light echo [Rest et al. 08, ApJ 680, 1137].

- [Kosenko et al. 08, A&A 490, 223] ⇒ O, Ne, Fe L, Mg from XMM RGS: no Ne/Mg in the ejecta; N from the ISM ⇒ ISM density, line broadening.
Spatial stratification in the ejecta (O/Si/Fe) [Kosenko et al. 10, A&A 519, 11] ⇔ spectral stratification (Tycho, 0509-67.5). Contrast: CC SNRs (Cas A)

- Fe/Si abundance ratios consistent with a normal SN Ia. No need for Ne, Mg.
Mn/Cr as a Metallicity Tracer

- With *Suzaku* we can detect the weak lines from elements like Mn and Cr in bright SNRs like Tycho [Tamagawa et al. 09 PASJ 61, 167].

- CO WDs have trace amounts of $^{22}\text{Ne}$ (relic from CNO cycle + He burning): 
  
  $$^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+,\nu_e)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne} \Leftrightarrow \eta = 1 - 2\left[\frac{Z}{A}\right] = 0.101xZ$$


- It is unclear how $\eta$ is affected by the simmering phase in the pre-explosion WD [Chamulak et al. 08, ApJ 677, 160].

- Outside the central $\sim 0.2\,M_\odot$ of ejecta, the Mn/Cr ratio is a good tracer of $\eta$, independent of explosion brightness ($^{56}\text{Ni}$ mass) ⇒ $Z \sim 0.05$ for Tycho.
Why Study Type Ia SNRs?

- Much of what we know about Type Ia SN progenitors comes from the stellar populations in their host galaxies ⇒ metallicities, ages, SFRs, SFHs.

- **Issues** [Manucci, Maoz talks]:
  - Measurements are not local ⇒ age and metallicity gradients.
  - By using supernova remnants (SNRs), it possible to study resolved stellar populations (RSPs) at the location of the SN progenitors ⇒ Milky Way, LMC, SMC, M31, M33...

**Key Window onto SN Ia progenitors!**
Core Collapse SNRs

SN 1994D in NGC 4526 (P. Challis)

N49
Z=0.008
Z=0.004
Z=0.0025
Z=0.001

SN 1987A
Z=0.008
Z=0.004
Z=0.0025
Z=0.001

N63A
Z=0.008
Z=0.004
Z=0.0025
Z=0.001

N158A
Z=0.008
Z=0.004
Z=0.0025
Z=0.001
**SNRs 0509-67.5 and N103B**

- **SNR 0509-67.5** was originated by a very bright Type Ia SN ($M_{56Ni} \sim 1M_\odot$). $\Delta m_{15} < 0.9$ [Rest et al. 08, ApJ 680, 1137] ⇒ $M_V \sim -19.5$. Yet, it is embedded in an old (7.9 Gyr) and metal-poor ($Z=0.0014$) stellar population.

- **SNR N103B**, on the other hand, is associated with vigorous SF in the recent past ($t<100$ Myr). Its morphology shows signs of interaction [Lewis et al. 03, ApJ 582, 770]. Maybe it had a young(er), more massive progenitor that lost a large amount of mass before the explosion.

No definitive claims about the progenitors can be made from the SFHs alone!
• There are **77 known SNRs in the MCs** (54 in the LMC, 23 in the SMC) ⇒ clean record of the environments where SNe explode.

• We don't know the **types** or the **ages**, we just know the **sizes**. Type is not a problem if DTD has enough resolution. **Age** is more delicate ⇒ **control time**.
• Use all available information to derive DTD (avoid a-posteriori statistics).

• SN rate ~ 1/200 to 1/500 yr, consistent with historical records [Badenes et al. 08 ApJ 680, 1149].

• 1st resolved stellar population DTD, but limited quality (only 77 SNe!).

<table>
<thead>
<tr>
<th>Density Tracer</th>
<th>Mean SNR Visibility [kyr]</th>
<th>[10^{-3} SN yr^{-1}]</th>
<th>[SNuM]</th>
<th>(\Psi_1^{a}) 0-35 Myr</th>
<th>(\Psi_2) [SNe yr^{-1} (10^{10} M_\odot)^{-1}]</th>
<th>(\Psi_3) (95% low lim.)</th>
<th>0.33-14 Gyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>13.3</td>
<td>4.1 ± 0.9</td>
<td>3.0 ± 0.7</td>
<td>2.86^{+0.66}_{-0.50}</td>
<td>0.389 ± 0.131</td>
<td>(&gt; 0.171)</td>
<td>&lt; 0.0014</td>
</tr>
<tr>
<td>SFR (Schmidt law)</td>
<td>22.5</td>
<td>2.4 ± 0.4</td>
<td>1.7 ± 0.3</td>
<td>2.86^{+0.43}_{-0.43}</td>
<td>0.091 ± 0.057</td>
<td>(&gt; 0.016)</td>
<td>&lt; 0.0014</td>
</tr>
<tr>
<td>H\alpha (Schmidt law)</td>
<td>13.9</td>
<td>3.3 ± 0.6</td>
<td>2.3 ± 0.4</td>
<td>2.86^{+0.54}_{-0.50}</td>
<td>0.194 ± 0.086</td>
<td>(&gt; 0.060)</td>
<td>&lt; 0.0016</td>
</tr>
<tr>
<td>No Scaling</td>
<td>13.4</td>
<td>5.8 ± 0.1</td>
<td>3.5 ± 0.7</td>
<td>2.86^{+0.61}_{-0.50}</td>
<td>0.316 ± 0.125</td>
<td>(&gt; 0.143)</td>
<td>&lt; 0.0024</td>
</tr>
<tr>
<td>HI+H\alpha</td>
<td>12.6</td>
<td>3.8 ± 0.8</td>
<td>2.6 ± 0.5</td>
<td>2.86^{+0.57}_{-0.50}</td>
<td>0.260 ± 0.100</td>
<td>(&gt; 0.104)</td>
<td>&lt; 0.0014</td>
</tr>
<tr>
<td>HI+SFR</td>
<td>15.9</td>
<td>3.1 ± 0.6</td>
<td>2.1 ± 0.4</td>
<td>2.86^{+0.51}_{-0.51}</td>
<td>0.165 ± 0.080</td>
<td>(&gt; 0.058)</td>
<td>&lt; 0.0013</td>
</tr>
</tbody>
</table>
In several Ia SNRs, Ca appears to be more ionized than Ar and Si (either wrt to 1D DDT models or in absolute terms) ⇒ shocked earlier, at higher density.

HV Ca??? [Mazzali et al. 05 ApJ 623, L37].

Badenes et al. 06, ApJ 645, 1373

Kosenko et al. 10, A&A 519, 11
Jacco's talk:

- No evidence for ionized bubbles (no “naked” SSSs).
- No evidence for fast accretion winds (lack of cavities).
- Ia SNRs are “well behaved” (spherical explosions/CSM).

At least one object (Kepler/SN1604) shows evidence for slow wind/non-conservative mass accretion.

This talk:

- X-ray spectra of Type Ia SNRs are well reproduced by $M_{\text{ch}}$ 1D DDT models (except maybe the spatial distribution of Ca).
- This can be used to determine the SN Ia subtype (dim/bright $\Leftrightarrow$ $^{56}\text{Ni} \Rightarrow \text{Fe}$). Two confirmations with light echoes (Tycho, SNR 0509-67.5).
- The key advantage of SNRs is the ability to study the environment: CSM + Resolved stellar populations.
- Mn/Cr ratio is a diagnostic for fundamental pre-explosion physics (neutron excess, progenitor metallicity?) [Borkowski talk].
SN 1994D in NGC 4526 (P. Challis)
• **CCD spectra** have been used to determine bulk yields and relative abundances ⇒ next step: Multi-D HD+NEI.

• **Non-dispersive high resolution spectroscopy of extended sources** will open new frontiers: local velocity measurements, disentangling the Fe L complex, measuring the metallicity of SN Ia progenitors...

Simulated IXO spectra of t~400 yr SNRs from a dim (blue) and bright (red) Type Ia SN.
Beware of statistics!

- It is extremely dangerous to overinterpret the results from single objects.

- Diffusion will affect SN progenitors on timescales of ~few 100 Myr.

- Watch out for a posteriori statistics.
• Homogeneous SNR catalog of 144 SNRs [Long et al. 10 ApJS 187, 495].
• Work in progress (w/ S. Trager and A. Monachesi).

Plot by A. Monachesi

Data from Massey et al. 06 AJ 131, 2478