Spectral Diagnostics in Type Ia SNRs

Carles Badenes (U. Pittsburgh)
We know very little about the progenitors of Type Ia SNe

- **Progenitor models:** single degenerate / double degenerate.

- **Direct clues** are scarce and ambiguous.

- **SN Ia** produce most of the Fe-peak elements in the Universe.

- **SNRs** are much closer than SNe and can be studied in greater detail.
SN Ia Progenitors: Clues

SN Ia are thermonuclear explosions of C/O WDs destabilized by accretion in binary systems.

- **Very little H** [Leonard 07].
- **Small** ($\sim R_{WD}$) [Nugent + 11, Bloom+ 11].
- **Faint** [Maoz & Mannucci 08, Li+ 11].
- **No early interaction** [Bianco+ 11].
- **Not much CSM near** [Hughes+ 07, Horesh+ 11, Chomiuk+ 11] or far [Badenes+ 06,07,08, Patnaude+ 12, but see Williams+ 11].
- **No bright companion left behind** [Kerzendorf+ 09, Schaefer+ 12].

Carles Badenes  
CfA  
August 10, 2012
Type Ia SNRs allow us to study SN Ia explosions and their progenitors in great detail.

- Detailed view of the ejecta structure thanks to the angular resolution of *Chandra*.
- Young SNRs might be still interacting with the CSM expelled by the SN progenitor.
- New perspective on SN Ia [Badenes 10].
The SNR road to Stockholm

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• **Phillips Relation:** Brighter SNe have broader LCs [Phillips 93].

• LCs powered by $^{56}\text{Ni}$ decay.

• Brighter SN Ia have more $^{56}\text{Ni}$ (up to $\sim 1 \ M_\odot$). They explode in star-forming galaxies [Sullivan+ 06].

• **Stratified ejecta:** Fe-peak nuclei on the inside, IMEs on the outside [Mazzali+ 07].

• **Explosive nucleosynthesis** in a C/O WD: deflagrations, detonations and delayed detonations [Nomoto+ 84, Thielemann+ 86].
SN Ia: Nucleosynthesis

- Burning regime controlled by peak temperature (and density) [Thielemann+ 86] ⇔ explosion physics.

- NSE (n-rich) / Incomplete Si burning / Incomplete O burning ⇒ ejecta stratification.
NEI Plasma in SNRs

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

- Cannot interpret the X-ray spectrum without understanding the bulk dynamics of the ejecta. Two approaches:
  - Simplify the hydro (e.g., plane shock models [Hughes+ 00, Borkowski+ 01]) ⇒ Relative abundances, $n_e t$, $T_e$ ⇒ Local plasma.
  - Full-fledged HD+NEI [Hamilton & Sarazin 84; Badenes+ 03; Sorokina+ 04] ⇒ Bulk yields ⇒ Compare to SN physics (so far, 1D!)
Tycho SNR

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

- See Badenes+ 03, 05.
- SN Ia brightness estimate based on 1D DDT models $\leftrightarrow M_{56\text{Ni}}$. These models work quite well.
- Tycho SNR: $M_{56\text{Ni}} = 0.74 M_\odot$ [Badenes+ 06], a normal SN Ia.
- Later confirmed by light echo spectroscopy [Rest+ 08, Krause+ 08].
- HD+NEI $\Rightarrow$ synthetic spectrum (APED)
• What are we doing here? We are making extremely crude comparisons between models and data (no $\chi^2$!!!).

• Given the uncertainties, we can only constrain the bulk properties of the SN ejecta!
Tycho SNR

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 ($\rho_{AM}=5e^{-25}$, $\beta=0.1$); $N_H=1.07$
• Underlying HD model must also make sense!!

• SNR 0509-67.5 \Rightarrow M_{56\text{Ni}} = 0.97 M_\odot [Badenes+ 08]. Also confirmed by the light echo [Rest+ 08].
• Kepler shows evidence for strong CSM interaction [Blair+ 91, Borkowski+ 92, 94, Reynolds+ 07].

• What does this mean? Not an isotropic stellar outflow! Maybe a small cavity? [Patnaude+ 12].
Mn and Cr: Why do we care?

- CO WDs have **trace amounts of** $^{22}\text{Ne}$ (relic from CNO cycle) [Timmes+ 03]
- $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+,\nu_e)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne} \iff \eta = 1 - 2\frac{Z_A}{A_A} = 0.101xZ$
- Outside the central $\sim 0.2 M_\odot$, Mn/Cr ratio traces $\eta$, independent of explosion brightness ($^{56}\text{Ni}$ mass).

![Diagram of nuclear reactions and elements]

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**Normalized Abundance**

<table>
<thead>
<tr>
<th>Element</th>
<th>Normalized Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Si</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>O/Ne</td>
<td>$1.0$</td>
</tr>
</tbody>
</table>

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**Legend**

- Proton
- Gamma Ray
- Neutron
- Neutrino
- Positron
Mn and Cr: Why do we care?

- **Mn/Cr mass ratio is insensitive to the explosion mechanism**, and behaves like \( Z^{0.65} \) [Badenes+ 08b].

- We need to infer the mass ratio from the flux ratios in X-ray spectra [Tamagawa+ 09].

![Graph showing Mn/Cr mass ratio insensitivity](image1)

![Graph showing flux ratios in X-ray spectra](image2)
Mn and Cr: Why do we care?

Filled: Halves with no rotation.

Open: Halves with a 45 deg rotation.

\[
\begin{align*}
\frac{f_{\text{Mn}}}{f_{\text{Cr}}} & \quad \frac{f_{\text{Ni}}}{f_{\text{Fe} \alpha}} & \quad \frac{f_{\text{Ni}}}{f_{\text{Fe} \beta}} & \quad \frac{f_{\text{Fe} \beta}}{f_{\text{Fe} \alpha}}
\end{align*}
\]

\[
\begin{align*}
\frac{f_{\text{Ni}}}{f_{\text{Fe} \alpha}} & \quad \frac{f_{\text{Fe} \beta}}{f_{\text{Fe} \alpha}}
\end{align*}
\]

are multiplied by 100.

Park+ in prep.
• Evidence for over-ionized Ca in several Ia SNRs.

• Tycho and 0509 from HD+NEI [Badenes+ 06,08].

• 0519 from plane shock model fits [Kosenko+ 11].

• What does this mean?
Some Thoughts (in lieu of Conclusions)

- We can explore **key parameters** like the **brightness of the explosion** ($^{56}$Ni mass), the **structure of the CSM**, and the **metallicity of the progenitor**.
- All this requires **good spectra and good atomic data**.
- Our approach to 'fitting' and 'measuring' needs to be revised.

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