Chemical Enrichment History Of Abell 3112 Galaxy Cluster Out To The Virial Radius

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### Chemical Enrichment by Supernova Explosions

- The types of supernova explosions (SNe) enriching the ICM can be broadly classified in two types; Type Ia (SN Ia) and core collapse (SN cc).

<table>
<thead>
<tr>
<th>Type</th>
<th>SN Ia</th>
<th>SN cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectra</td>
<td>Si, S, Fe, Ni</td>
<td>O, Ne, Mg, Si</td>
</tr>
<tr>
<td>Explosion</td>
<td>Thermonuclear explosion</td>
<td>Core-collapse</td>
</tr>
<tr>
<td></td>
<td>(low-mass stars)</td>
<td>(massive stars)</td>
</tr>
<tr>
<td>SN Yields</td>
<td>W7 &amp; W70 (^{(I99)})</td>
<td>10-50 M(^\odot) (^{(I99)})</td>
</tr>
<tr>
<td></td>
<td>WDD &amp; CDD (^{(I99)})</td>
<td>0-1.0 Z(^\odot) (^{(I99)})</td>
</tr>
<tr>
<td></td>
<td>CDDT &amp; ODDT (^{(M10)})</td>
<td></td>
</tr>
</tbody>
</table>

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Methodology

**A Robust Model to Constrain Supernova Fractions: SNapec Model**

- A newly developed XSPEC model which determines the total number of supernova explosions and the ratio of SN Ia to SN cc supernova explosions by directly fitting the X-ray spectra.

- **snapec** combines *apec* with all up-to-date relative abundance scenarios (~122).

- The model derives the mass of the i-th element in terms of:

\[
\frac{Z_i^{SN}}{Z_i^\odot} = \frac{N_i^{SN}}{M_i^\odot (1 + R)} [R y_i^{Ia} + < y_i^{cc}>] 
\]

\[
M_i^\odot \approx \frac{M_{ICM} Z_i^\odot A_i}{m_N}
\]

\[
R = \frac{N^{Ia}}{N^{cc}}
\]

- It has five parameters:

- **kT**: Temperature
- \(N^{SN}\): Total number of SN explosions
- **R**: SN Ratio
- **SNIModIndex**: Type Ia SN yields
- **SNIIModIndex**: Core Collapse SN yields
- **z**: The cluster’s redshift
- **Norm**: Emission measure

*Snapec*: Bulbul et al., The Astrophysical Journal, 753, 1, 2012
Abell 3112

- Abell 3122 is an archetypal relaxed cool core cluster at redshift 0.0752, making it ideal target for studying its chemical enrichment history.
Results

Results 1: Global Spectral Properties: 1T $apec$ Model

*The best fit parameters of Suzaku observations, $1\sigma$ statistical errors together with systematics are over-plotted.

The First Time Measurements in literature

*Ezer et al., The Astrophysical Journal, 836, 1, 2017
Results

Results 2: Global Spectral Properties: 1T Vapec Model

- We further investigate the radial abundance distributions of individual $\alpha$-elements, such as silicon (Si), sulfur (S), iron (Fe), and magnesium (Mg) out to $R_{200}$.

- The Fe, Si, S, and Mg elemental abundances are allowed to vary independently while other elemental abundances are fixed to the measured Fe abundance at the outskirts, $0.25Z_\odot$.

*Ezer et al., The Astrophysical Journal, 836, 1, 2017
Results

Results 3: Chemical Enrichment History: SNapec Model

- To investigate chemical enrichment history out to $R_{200}$ of Abell 3112, we fit the innermost spectra (Region 1) with 1T snapec model for various SN yields.

Table 1: Best Fit parameters of snapec model for the innermost (0' - 2') region.

<table>
<thead>
<tr>
<th>SN Ia Model</th>
<th>$N_{SNe} \times 10^9$</th>
<th>$R (N_{Ia}/N_{cc})$</th>
<th>C-stat (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W7</td>
<td>$3.61 \pm 0.16$</td>
<td>$0.10 \pm 0.01$</td>
<td>1112.4 (840)</td>
</tr>
<tr>
<td>W70</td>
<td>$3.59 \pm 0.25$</td>
<td>$0.10 \pm 0.02$</td>
<td>1108.9</td>
</tr>
<tr>
<td>WDD</td>
<td>$3.24 \pm 0.10$</td>
<td>$0.12 \pm 0.02$</td>
<td>1108.1</td>
</tr>
<tr>
<td>CDD</td>
<td>$3.18 \pm 0.15$</td>
<td>$0.12 \pm 0.01$</td>
<td>1108.8</td>
</tr>
<tr>
<td>CDDT</td>
<td>$3.08 \pm 0.28$</td>
<td>$0.41 \pm 0.09$</td>
<td>1173.3</td>
</tr>
<tr>
<td>ODDT</td>
<td>$3.06 \pm 0.21$</td>
<td>$0.18 \pm 0.03$</td>
<td>1112.3</td>
</tr>
</tbody>
</table>

We find that 1D delayed detonation WDD model for SN Ia is the best describing the Suzaku data of the immediate core region.

The 2D delayed detonation symmetric CDDT model can at best achieve fits that are less significant than other models, suggesting they are not a dominant process enriching the ICM.
Results

Results 3: Chemical Enrichment History: SNapec Model

- To determine the distribution of SN fraction out to $R_{200}$ rather than individual testing, we use WDD model which gives the best fit for the highest signal-to-noise region.

Table 2*: Best Fit parameters of snapec model parameters with 1σ statistical and systematic uncertainties are added in quadratures.

<table>
<thead>
<tr>
<th>SN Models</th>
<th>Regions (arcmin)</th>
<th>$N_{SN} \times 10^9$</th>
<th>R</th>
<th>C-stat (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN Ia: WDD (I99)</td>
<td>0' - 2'</td>
<td>3.24 ± 0.10</td>
<td>0.12 ± 0.02</td>
<td>1108.1 (840)</td>
</tr>
<tr>
<td>SN cc:10-50 M⊙, 0-1 Z⊙ (I99)</td>
<td>2' - 4'</td>
<td>1.96 ± 0.36</td>
<td>0.16 ± 0.02</td>
<td>1079.9 (842)</td>
</tr>
<tr>
<td></td>
<td>4' - 6'</td>
<td>1.48 ± 0.13</td>
<td>0.12 ± 0.04</td>
<td>1008.9 (850)</td>
</tr>
<tr>
<td></td>
<td>6' - 8'</td>
<td>1.22 ± 0.12</td>
<td>0.13 ± 0.05</td>
<td>337.3 (259)</td>
</tr>
<tr>
<td></td>
<td>8' - 18'</td>
<td>0.87 ± 0.17</td>
<td>0.11 ± 0.06</td>
<td>244.2 (151)</td>
</tr>
</tbody>
</table>

*Ezer et al., The Astrophysical Journal, 836, 1, 2017
Results 3: Chemical Enrichment History: SNapec Model

The ratio of SN Ia to SN cc is fairly **uniform** from the core to the outskirts.

\*Ezer et al., The Astrophysical Journal, 836, 1, 2017
Conclusions

• Deep Suzaku (1.2 Ms of total XIS exposure) and Chandra (72ks) observations of Abell 3112.

• Global spectral features with single and multi temperature structure: temperature peaks around ~ 4.8 keV and declines to 3.37 keV in the virial radius.

• The metallicity of the ICM: $0.22 \pm 0.08 \, Z_{\odot}$ (near the virial radius) consistent with Virgo & Perseus. Uniform Fe profile at radius $> 0.2R_{200}$.

• Snapec (XSPEC model) for calculation of SN Ia to SN cc ratio.

• Our results favor 1D W7, CDD, and WDD SN Ia models. (A 2D delayed detonation SN Ia model CDDT produces less significant fits compared to priors, overestimate the observational Si abundance).

• The fractional distribution of the SN Ia ($I99 \, WDD$) to SN cc between $0.12–0.16$. (In agreement with the observed fraction in our Galaxy!)

• The distribution of the SN Ia fraction is fairly **UNIFORM** out to $R_{200}$ indicating:
  • Metal enrichment at an early epoch ($z \sim 2–3$)
  • Mixing originating from an intense period of star formation activity
  • Metals are well-mixed into the ICM
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