Progenitor Metallicity of Kepler’s Supernova

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Outline

1. Motivation: Nucleosynthesis study of Type Ia SN
2. Progenitor Metallicity of SNe Ia: Why Kepler?
3. Initial Suzaku Results of Kepler (100 ks, AO2)
4. **Suzaku Key Project of Kepler (AO4-5)**
   - Preliminary results
Type Ia Supernova

- Thermonuclear explosion of C/O white dwarf (WD) in a close binary:
  complete destruction of a star
  → Major source of Fe-group elements: galactic chemical evolution
  → “Standard candles” for cosmology
- Type Ia SNe are not homogeneous:
  Various physical mechanisms of explosion & nucleosynthesis (e.g.,
  Iwamoto+ 1999): Detonations, deflagrations, delayed detonations etc.
  => yield diverse compositions of burning products.
  Various evolutionary paths or ages (prompt, delayed) related to progenitor
  mass, metallicity, and circumstellar structure (e.g., Scannapieco & Bildsten
  2005; Aubourg+ 2007; Matteucci+ 2009)
  => affect SN light curve and luminosity (e.g., Timmes+ 2003).
  Various nature of the WD binary system: normal or WD companion.
  => accretion vs merger.
Type Ia SN Populations


**Prompt:** Younger progenitors, brighter SNe Ia (e.g., 1991T), SN rate $\propto$ star-formation rate

**Delayed:** Older progenitors, dimmer SNe Ia (e.g., 1991bg), SN rate $\propto$ total stellar mass

Actual progenitors have never been identified: Tycho (SN 1572) might have been a prompt pop with a non-subsolar metallicity? (Badenes+ 2008).

Model by Scannapieco & Bildsten (2005)
Metallicity of SN Ia Progenitor

- Metallicity ($Z$) of SN Ia progenitor is a key parameter to affect age/mass CSM (prompt vs delayed SN Ia populations) of the progenitor.

- C/O WDs born from intermediate mass stars that burn H through the CNO cycle which ends up with $^{14}$N.

- Neutron excess ($\eta = 1 - 2Y_e = 1 - 2[Z_A/A]$, $Z_A =$ atomic number, $A =$ atomic mass) is dominated by $e$-capture at the core ($M < 0.2 \, M_{\odot}$) (e.g., Brachwitz+ 2000).

- At $M \sim 0.2-0.8 \, M_{\odot}$, $^{14}$N $\rightarrow ^{18}$F $\rightarrow ^{18}$O $\rightarrow ^{22}$Ne (He-burning), thus $\eta$ is directly related to $Z$: $\eta = 0.101 \times Z$ (Timmes+ 2003).

- $\eta$ is efficiently stored in trace elements with unequal numbers of $p$, $n$ ($^{55}$Co $\rightarrow ^{55}$Mn).

- An abundant element Mn is useful. Cr is an ideal reference element: it is the same incomplete Si-burning product as Mn, but insensitive to $\eta$, ($^{52}$Fe $\rightarrow ^{52}$Cr).
$Z$ vs $M_{Mn} / M_{Cr}$ in SN Ia

Mn to Cr mass ratio is an excellent tracer of metallicity of the progenitor:

$$M_{Mn} / M_{Cr} = 5.3 \times Z^{0.65}$$

(Badenes+ 2008)
Measuring $M_{\text{Mn}} / M_{\text{Cr}}$ Ratio

SN Ia nucleosynthesis study of trace elements

- X-ray data of young SNRs effectively reveal SN nucleosynthesis products directly from the stellar interior.
- **Line flux measurements** Cr & Mn in the X-ray spectrum of young Type Ia SNR *(Tamagawa+ 2008).*

\[
M_{\text{Mn}} / M_{\text{Cr}} = 1.057 \times \left( \frac{f_{\text{Mn}}}{f_{\text{Cr}}} \right) / \left( \frac{\varepsilon_{\text{Mn}}}{\varepsilon_{\text{Cr}}} \right),
\]

\[f = \text{line flux}, \ \varepsilon = \text{specific emissivity per ion} \ (Badenes+ 2008)\]

- Extragalactic SNe are not useful:
  - Long half-life of $^{55}\text{Fe}$ (~2.7 yr): parent nucleus of $^{55}\text{Mn}$
  - Difficult to reveal/study CSM and ambient environment
    → Must be young Type Ia SNRs
Why Kepler?

- SN 1604, Type Ia:
  - Fe-rich ejecta, No O-rich ejecta
  - Balmer-dominated shocks
  - No central point source

- Shock-CSM interaction (e.g., Dennefeld 1982; Reynolds+ 2007):
  - Wind-modified CSM due to progenitor (or companion) star?

- High $z \sim 500$ pc, a runaway massive progenitor?
  - Unique opportunity to study nature of the progenitor with both metallicity and CSM structure!

750 ks Chandra
(Reynolds+ 2007)

Red: 0.3-1.72 keV
Green: 0.72-1.7 keV
Blue: 1.7-8 keV
Kepler: Initial Suzaku Results

- Mn & Cr lines are detected:
  cf. It is unclear with Chandra 750 ks.
  → Suzaku XIS is uniquely efficient!
  But faint. Large statistical uncertainties.

- Due to the bright emission of Kepler, source-free regions on the same XIS are not fully reliable to estimate the background. Thus, we tested Mn and Cr line flux measurements with several background spectra.
  → Large systematic uncertainties.
$M_{\text{Mn}} / M_{\text{Cr}} < 1.5$.

Metallicity ($Z$) is not constrained because of poor photon statistics & systematic uncertainties in the background estimates.
Suzaku Key Project of Kepler

- The initial results are limited by poor photon statistics and uncertain background estimates. Both a deep exposure of Kepler and a background pointing are essential to constrain the metallicity of progenitor.

- **Suzaku Key Project (AO4-5):**
  620 ks source + 240 ks background observations were performed in 9/2009 – 4/2011: to minimize both statistical (due to poor photon statistics) and systematic (due to background characterization) uncertainties. The goal was to place a tight constraint on $M_{\text{Mn}} / M_{\text{Cr}}$ ratio, thus on the progenitor metallicity ($Z$) within a factor of $\sim 2$ to distinguish solar vs supersolar abundances.
Suzaku Key Project of Kepler

- Four background pointings of nearby source-free regions within ~1.5° of Kepler were performed:

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Kepler KP Results: Preliminary

\( f_{\text{Mn}} = 4.99 \pm 1.15 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} (2\sigma) \)

\( f_{\text{Cr}} = 8.31 \pm 1.20 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \)

[Also, Ni K\( \alpha \) \((E = 7.53 \text{ keV}, \sim 12\sigma)\) and Fe K\( \beta \) \((E = 7.12 \text{ keV}, \sim 16\sigma)\) lines are detected.]

\[
\frac{M_{\text{Mn}}}{M_{\text{Cr}}} = 1.057 \left( \frac{f_{\text{Mn}}}{f_{\text{Cr}}} \right) \left( \frac{\varepsilon_{\text{Mn}}}{\varepsilon_{\text{Cr}}} \right) = 0.92^{+0.55}_{-0.36}
\]

(where \( \varepsilon_{\text{Mn}}/\varepsilon_{\text{Cr}} = 0.69 \pm 0.14 \), for \( kT \sim 5 \text{ keV} \))

\[
M_{\text{Mn}} / M_{\text{Cr}} = 5.3 Z^{0.65} \quad (\text{Badenes} + 2008)
\]

\[ \Rightarrow \quad Z = 0.068 \]

With \( Z_{\odot} = 0.017 \quad (\text{Anders & Grevesse 1989}), \)

\[ \Rightarrow \quad \frac{Z}{Z_{\odot}} = 4.0^{+4.2}_{-2.1} \]
$M_{\text{Mn}}/M_{\text{Cr}}$ ratio in Kepler reveals a significantly overabundant $Z/Z_\odot \sim 4$.

→ This high metallicity of the progenitor supports a young, prompt SN Ia for Kepler.

(“C-simmering” unlikely affects Kepler because it was a high-$Z$ star with no evidence of sub-luminous SN.)

More to come: Test with other spectral models (measuring $T$, abundances etc)
Implications by Fe and Ni
Better constraint on ion emissivity?
Comparison with update from Tycho (400 ks XIS):
→ $Z_{\text{Kepler}} > Z_{\text{Tycho}}$?
→ Different or same population(s)?