Linking 91T-like and Ia-CSM SNe from Observations of SNRs

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[Ia-CSM] SN Ia showing evidence for circumstellar (CS) interactions. SN Ia + narrow H lines $\rightarrow$ existence of a companion star $\rightarrow$ SD.

SN 2002ic (Hamuy et al. 2003)
91T-like + CS = Ia CSM (SN IIIn)?

\[ f = \frac{f_{\text{SN}}}{f_{\text{BB}}} \]

\( \sim 1 \) for 91T-like
\( \sim 0.5 \) for Ia-CSM
\( \sim 0.05 \) for SN IIIn

\( \text{Ia CSM} = (91T\text{-like}) + \text{(blackbody)} + \text{(narrow lines)} \)

Aldering et al. (2006)

→ 91T-like and Ia CSM originate from the same SD progenitor?
PTF11kx initially looked like 91T, later evolved into Ia CSM that shows strong narrow lines.

Bridging the observational gap between 91T and Ia CSM

Dilday et al. (2012)
SNRs as Extremely Late-Phase SNe

E.g., Tycho’s SNR (SN 1572)
Age ~ 450 yr
→ 1000x larger than SNe
Radius ~ $1 \times 10^{19}$ cm
→ 1000x larger than SNe

Detection of CSM (if any) would be the case of extremely late-phase CSI.
Optical, IR, X-ray observations revealed CSM from a progenitor: Dense ($n \sim 100 \, \text{cm}^{-3}$) N-rich ($N/H \sim 4 \times \text{solar}$) knots (e.g., Blair+1991; 2007; SK+2015)

→ Was Kepler’s SN a 91T-like SN or Ia CSM, or something else?

How to know the SN types of SNRs?
Light-Echo Spectra → Subtyping

Tycho’s SNR
(age ~ 450 yr)

Light-echo spectrum

Krause et al. (2008)

→ Normal Ia

SNR 0509-67.5
(age ~ 400 yr)

Light-echo spectrum

Overluminous

Good match!

Rest et al. (2008)

→ Overluminous Ia

Tycho’s SNR
(age ~ 450 yr)

Light-echo spectrum

Krause et al. (2008)

→ Normal Ia

SNR 0509-67.5
(age ~ 400 yr)

Light-echo spectrum

Overluminous

Good match!

Rest et al. (2008)

→ Overluminous Ia
The Fe/IME ratio: **0509 >> Tycho** → Consistent with the light-echo result.

Fe/IME ratio can be a good discriminator of SN Ia subclassification, agreeing with pioneering work for SNe Ia by Mazzali et al. (2007)
Comparison of X-Ray Spectra

Fe lines from Kepler are very strong!

Suzaku XIS (FI)
Data:
- XMM-Newton RGS (< 2keV)
- Suzaku XIS (> 2 keV)

Model:
1) vpshock
   (swept-up medium)
2) 3 vnei
   (ejecta)
3) power-law
   (synchrotron)

→ Resulted in reasonable fits.
Ejecta Masses

Kepler is well within overluminous Ia.

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<thead>
<tr>
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<th>IME</th>
<th>IGE</th>
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<tbody>
<tr>
<td>Kepler</td>
<td>0.12</td>
<td>0.95</td>
</tr>
<tr>
<td>0509</td>
<td>0.34</td>
<td>0.75</td>
</tr>
<tr>
<td>Tycho</td>
<td>0.70</td>
<td>0.35</td>
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\[\text{IME} + \text{IGE} = 1.05 \, M_\odot\]

\[\uparrow\text{Including unshocked IGE, based on the assumption that } M_{\text{IME}} + M_{\text{IGE}} = 1.05 \, M_\odot\] (Mazzali et al. 2007).
The light curve is consistent with 91T (or on the Phillips relation), but not Ia-CSM.

NB: Ruiz-Lapuente (2017) argued that the light curve looks like a normal Ia.
Kepler’s SN = Ia-CSM showing Extremely-Late CS Interactions

Kepler’s SN
1) 91T-like (possibly)
2) CSM interactions started ~300 yr after the SN explosion

This result supports the recent argument by Leloudas et al. (2015) that overluminous Ia and Ia-CSM are fundamentally the same objects (SD cases). (We need a light-echo spectrum from Kepler’s SN!)
N103B in the LMC

Age ~ 700 yr

Dense (~45 cm$^{-3}$) gas in the west

The IR spectra from N103B and Kepler are very similar with each other!

→ CSM from a relatively young and massive progenitor, not an AGB or RGB, because there is no evidence for N enhancements.

Williams et al. (2014)
Spectral Fitting

Counts s\(^{-1}\) keV\(^{-1}\) cm\(^{-2}\)

Swept-up medium
Ejecta 1 (Fe L lines)
Ejecta 2 (IME’s K lines)
Ejecta 3 (pure Fe)
Powerlaw ($\Gamma = 2.5$ fixed)

Chandra ACIS
for pure CSM region
(local-BG subtracted)

Energy (keV)
0519-69.0 in the LMC

Swept-up medium
Ejecta 1 (Fe L lines)
Ejecta 2 (IME’s K lines)
Ejecta 3 (pure Fe)
Powerlaw ($\Gamma = 2.5$ fixed)

Age $\sim 600$ yr

H$\alpha$ O VII (0.3-0.6 keV) Fe L (0.7-0.9 keV)

Chandra ACIS (local-BG subtracted CSM)
Comparison of X-Ray Spectra

- Tycho (absorption corrected for LMC) – normal Ia
For stars with $L > 2.6 L_\odot$, no peculiar objects (in velocity, rotation, metallicity) were found. → ruling out SD.

27 main-sequence stars brighter than $m_v = 22.7$ show no peculiar features in velocity and rotation. → ruling out SD.

Ruiz-Lapuente et al. (2018)

Edwards et al. (2012)
A link between Ia-CSM and 91T-like was supported by observations of SNRs. Therefore, these two types may be of the same SD origin.

We argue that IGE/IME ratios can classify subtypes of Ia SNRs, based on Tycho and 0509.

Application to Kepler’s SN suggests a 91T-like SN.

The existence of CSM in Kepler’s SNR strongly supports the idea that 91T-like and Ia-CSM SNe have the same SD origin.

The other two Ia SNRs with CSM (N103B and 0519) seem to have originated from 91T-like SNe.
Companion Survey in N103B

Li et al. (2017)

The star #1 (closest to the center of Hα filaments) could be a companion candidate.
Strong N Ly$\alpha$ $\Rightarrow$ N/H = 6 ± 3 solar
The mass of diffuse CSM: $\sim$0.3 M$_\odot$
$\Rightarrow$ $\dot{M}$ $\sim$1.5x10$^{-5}$ ($V_w/10$ km s$^{-1}$) M$_\odot$ yr$^{-1}$

Consistent with AGB star wind properties

But, a bright companion star is not yet found (Kerzendorf+2014; Luiz-Lapuente+2018).
0519 (Age \sim 600 \text{ yrs})

Swept-up medium
Ejecta 1 (L lines)
Ejecta 2 (IME’s K lines)
Ejecta 3 (pure Fe)
Powerlaw ($\Gamma = 2.5 \text{ fixed}$)
X-Ray Emitting Regions

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<tr>
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<th>IME-rich layer</th>
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<tr>
<td>Kepler (=0509)</td>
<td>0.7 $R_{fs}$ -- 0.85 $R_{fs}$</td>
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