Hunting the Progenitors of Supernovae Type Ia

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Supernova Type Ia (SNIa) play a key role in stellar and galaxy evolution and cosmology

- Distance indicators
- Element factories
- Cosmic-ray accelerators
- Kinetic energy sources
- Endpoints of stellar binary evolution

SNIa occur at a rate of $\sim 30$/s in the observable universe, but identification of what is exploding remains unknown - this is the outstanding mystery in the field.
SNIIa are defined by their spectra:
1) the lack of hydrogen lines
2) a strong Si II absorption feature
Once defined, here are several observational characteristics which may help in the search for progenitors:

Nearly 90% of all SNIa form a homogeneous class in terms of their spectra, light curves, and peak absolute magnitudes.
Near maximum light, spectra are characterized by O-Ca at high velocity (8k-30k km s$^{-1}$).

In the late, nebular phase, the spectra are dominated by lines of iron.
There exist a number of correlations between different pairs of observables, including one between the absolute magnitude and the shape of the light curve.

![Graph showing correlations between Luminosity and Time](image)

- Expansion and Diffusion time scales about equal
- Optical light curve
- $^{56}\text{Ni} + ^{56}\text{Co}$ decay
- $\sim 0.6 \, M_\odot$ of $^{56}\text{Ni}$ for a typical SNIa
- $\gamma$-ray escape
Brighter is broader.

This can be used to correct for intrinsic variations in the peak luminosity to give a standard candle.

After correction, the dispersion in luminosity distance is $\leq 7\%$. 

\[
M_V - 5 \log \left( \frac{h}{65} \right)
\]
Tycho Supernova Remnant: NASA’s Spitzer, Chandra, & Spain’s Calar Alto

- Green & Yellow - iron and silicon
- Blue - shocked electrons
- Red - dust

Age: 442 years
Distance: ~ 7500 ly
Diameter: ~ 0.8’ (18 ly)
Expansion: ~ 0.3”/year
A successful model starting from a carbon+oxygen white dwarf must make

0.1 - 1.0 M☉ $^{56}\text{Ni}$ for the light curve

0.2 - 0.4 M☉ Si, S, Ar, Ca for the spectrum

$< 0.1$ M☉ $^{54}\text{Fe} + ^{58}\text{Ni}$ for the nucleosynthesis

Not too much O close to $^{56}\text{Ni}$ for the spectrum

Allow for some diversity for fun
Planetary Nebula:
Tosses off Hydrogen and Helium Layers

Runs out of Helium fuel

Main Sequence

Helium Burning to Carbon

Helium Ignites

Red Giant

Carbon-Oxygen White Dwarf in 10 billion years

H → He

He

C+O

H

He

H He H He C+O
The relative frequency of these channels is unknown.
Standard paradigm single-degenerate pathway:

- accretion
- simmering
- ignition
- subsonic flame

Instabilities
detonation?
supernova

Hardy 2006
Dursi et al 2001
NKG 2004
Röpke 2001
Zingale et al 2006
LANL 1945
NASA
Standard double-degenerate merger pathway:

- **Binary birth**
  - Secondary star
  - Bridge
  - Primary star
  - Spiral arm

- **Common envelope #1**
  - Circumsecondary Disk

- **Common envelope #2**

**Angular momentum loss**

**Surface detonation?**

**Supernova**

*Guillochon et al. 2010*
A double-degenerate collision pathway:

triple star system

Newtonian dynamics

$e \geq 0.999999$

3 body problem

supernova

Katz et al 2013
Variations in the peak luminosity may originate in part from a scatter in the composition of the main-sequence stars that become white dwarfs.
A main-sequence star's initial metallicity comes from the CNO and $^{56}$Fe inherited from its ambient interstellar medium.

All the CNO piles up at $^{14}$N during hydrogen burning, because $^{14}$N(p,g) is the slowest step in the CNO cycle.

During helium burning all of the $^{14}$N is converted into $^{22}$Ne by $^{14}$N (a,g) $^{18}$F ($\beta^+,\nu_e$) $^{18}$O (a,g) $^{22}$Ne.

Pileups at $^{14}$N and $^{22}$Ne have been repeatedly verified for ~40 years. This is standard stellar evolution.
Mass and charge conservation set the white dwarf’s neutron enrichment.

\[ \sum_{i=1}^{n} X_i = 1 \quad Y_e = \sum_{i=1}^{n} \frac{Z_i}{A_i} X_i \]

\[ X^{(22\text{Ne})} = 22 \left[ \frac{X^{(12\text{C})}}{12} + \frac{X^{(14\text{N})}}{14} + \frac{X^{(16\text{O})}}{16} \right] \]

\[ Y_e = \frac{10}{22} X^{(22\text{Ne})} + \frac{26}{56} X^{(56\text{Fe})} + \frac{1}{2} \left[ 1 - X^{(22\text{Ne})} - X^{(56\text{Fe})} \right] \]

Assuming the $^{22}\text{Ne}$ and $^{56}\text{Fe}$ are uniformly distributed.
SNIa models make most of their $^{56}\text{Ni}$ in nuclear statistical equilibrium between 0.2 - 0.8 $M_{\odot}$, where weak reactions don’t change the number of neutrons since they occur on time-scales longer than the explosion.

W7-like, Nomoto et al. 1984
If $^{56}\text{Ni}$ and $^{58}\text{Ni}$ are the only species in NSE, mass and charge conservation imply a linear relationship between the mass fraction of $^{56}\text{Ni}$ and $Y_e$:

$$X(^{56}\text{Ni}) = 1 - X(^{58}\text{Ni}) = 58Y_e - 28$$

We can set the final $Y_e$ equal to the initial $Y_e$ of the white dwarf since weak interactions are not dominant where most of the $^{56}\text{Ni}$ is made.

$$X(^{56}\text{Ni}) = 1 - 0.057 \frac{Z}{Z_\odot}$$
Explosion models confirm the analytical result.

\[ M(^{56}\text{Ni}) = M(^{56}\text{Ni})_{Z=0} \left[ 1 - 0.057 \frac{Z}{Z_\odot} \right] M_\odot \]
Constraining a metallicity dependence is challenging:
1) assumes galaxy metallicity = supernova metallicity
2) may be a stronger dependence on mean stellar age

Observations find consistency with the analytical result, but the trend is smaller than predicted and there is considerable scatter.

Constraining a metallicity dependence is challenging:
1) assumes galaxy metallicity = supernova metallicity
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The SPIDER Network

Initial Focused Efforts:
- Massive Main Sequence Stars
- Evolved Massive Star Envelopes
- Red Giant Asteroseismology
- Carbon Burning Flames

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If the composition of the white dwarf has an observable effect on the $^{56}\text{Ni}$ production and thus the SNIa light curve, it could have an effect on other elements as well.

From observed Si, S, Ca, and Fe abundances, we have developed a new tool which applies the QSE relations (in reverse!) to determine all the abundances and a measure of $Y_e$ in the silicon group regions of individual SNIa.
The method begins with mass & charge conservation, and the constraints for a two-cluster QSE:

\[ Y_n + Y_p + 28Y_{28\text{Si}} + 32Y_{32\text{S}} + 40Y_{40\text{Ca}} + 54Y_{54\text{Fe}} + 58Y_{58\text{Ni}} = 1 \]

\[ Y_p + 14Y_{28\text{Si}} + 16Y_{32\text{S}} + 20Y_{40\text{Ca}} + 26Y_{54\text{Fe}} + 28Y_{58\text{Ni}} = Y_e \]

\[ Y_{\text{SiG}} = Y_{28\text{Si}} + Y_{32\text{S}} + Y_{40\text{Ca}} \quad \quad Y_{\text{FeG}} = Y_{54\text{Fe}} + Y_{58\text{Ni}} \]
Then, from the defining QSE relations:

\[
\frac{Y_{A,Z}}{Y_{A',Z'}} = f(\rho, T) Y_p^{Z-Z'} Y_n^{A-A'} -(Z-Z')
\]

\[
f(\rho, T) = \frac{G_{A,Z}}{G_{A',Z'}} \left( \frac{\rho N_A}{\theta} \right)^{A-A'} \exp \left( \frac{B - B'}{kT} \right)
\]

\[
\theta = \left( \frac{m_u kT}{2\pi \hbar^2} \right)^{\frac{3}{2}}
\]
We derive our first (nearly trivial) result

\[ \Phi(T) = \frac{Y_{28\text{Si}}}{Y_{32\text{S}}} \left( \frac{Y_{40\text{Ca}}}{Y_{32\text{S}}} \right)^{1/2} = \exp \left( \frac{-1.25}{T_9} \right) \]

Measuring \( \Phi \) at a single epoch from the abundance ratios allows a test of whether the SiG material was produced in a QSE state.

Measuring \( \Phi \) at multiple epochs when silicon features dominate the spectrum allows trends in the QSE temperature to be assessed.
Measurement of four quantities $Y_{28\text{Si}}$, $Y_{32\text{S}}/Y_{28\text{Si}}$, $Y_{40\text{Ca}}/Y_{32\text{S}}$, $Y_{54\text{Fe}}/Y_{28\text{Si}}$ is a sufficient basis to solve for all the abundances in the silicon-rich region of SNIa.

$$Y_e = Y_{28\text{Si}} \left[ 14 + 16 \frac{Y_{32\text{S}}}{Y_{28\text{Si}}} + 20 \frac{Y_{40\text{Ca}}}{Y_{32\text{S}}} \frac{Y_{32\text{S}}}{Y_{28\text{Si}}} + 26 \frac{Y_{54\text{Fe}}}{Y_{28\text{Si}}} + 28 \Psi \frac{Y_{32\text{S}}}{Y_{28\text{Si}}} \frac{Y_{54\text{Fe}}}{Y_{28\text{Si}}} \right]$$

Accurate determination of $Y_{28\text{Si}}$, $Y_{32\text{S}}/Y_{28\text{Si}}$, $Y_{40\text{Ca}}/Y_{32\text{S}}$, and $Y_{54\text{Fe}}/Y_{28\text{Si}}$ is sufficient to determine $Y_e$ to $\sim 6\%$ because these abundances account for $\sim 94\%$ the QNSE composition.
Synthetic spectra for the W7-like models with 0 to 4 times solar 22Ne.
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Advances (plus a little serendipity) over the next decade should enable us to decipher the progenitors of Supernovae Type Ia.

1) Different Si, S, Ca ratios
2) Tidal tails
3) Significant unburned carbon + oxygen
4) Early gamma-ray light curve or line profiles
5) Narrow HI in emission or absorption
6) Interaction with circumstellar medium in radio or x-rays
7) Frequency of SN Ia as a function of redshift