On the peak luminosity of type Ia supernovae and the dark energy equation of state

Frank Timmes
Roadmap

1) Why the intrinsic variations?

2) Going deeper by going simpler

3) Likely future endeavors
For nearby supernovae, the variation in peak luminosity is \( \sim 3 \).

For more distant events, there are several sub-luminous events which broaden the variation to about a factor of 10.
Brighter light curves are broader.

This relationship can compensate for intrinsic variations in peak luminosity to give a standard candle.

After correction, the dispersion in optical light curves is $\sim 15\%$. 
While SNIa are used to measure the history of cosmic expansion, the exact mechanism leading to these explosions remains unclear.
Let’s re-explore the idea that variations in the peak luminosity originate in part from a scatter in the metallicity of the main-sequence stars that become white dwarfs.
A main-sequence star's initial metallicity comes from the CNO and $^{56}\text{Fe}$ nuclei inherited from its ambient interstellar medium.

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

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

Pileups at $^{14}\text{N}$ and $^{22}\text{Ne}$ 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.
SNII models make most of their $^{56}\text{Ni}$ in NSE 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.
In NSE, if $^{56}\text{Ni}$ and $^{58}\text{Ni}$ are the only species, mass and charge conservation imply a linear relationship between the mass fraction of $^{56}\text{Ni}$ and $Y_e$:

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

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

$$X(\text{Ni}) = 1 - 0.057\frac{Z}{Z_\odot}$$
ID models confirm our analytical result.

\[ M(^{56}\text{Ni}) = M(^{56}\text{Ni})_{Z=0} \left[ 1 - 0.057 \frac{Z}{Z_{\odot}} \right] M_{\odot} \]

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.” - Tommy Gold
Multi-D models find $^{56}\text{Ni}$ variations of 2\% from C/O ratios, 7\% from the central density, and 20\% from metallicity - consistent with our analytics.
Until the last 2 months, observations of a metallicity trend have been less compelling. Not clear if this is caused by the lack of an effect or that the techniques used so far do not have the required level of precision.

Ivanov et al. 2000

Ellis et al. 2007
Gallagher et al (2008) compared absorption-line strengths of 29 E/S0 galaxies which hosted SNIa and found galaxies with high iron abundances host less luminous SNIa, consistent with our analytical prediction.

More controversial was their finding of a significant trend of distance residuals ($m_z - m_{SN}$) with host-galaxy metal abundance.
Howell et al (2008) used SNLS data with the Tremonti et al. (2004) mass-metallicity relation. They report our analytical result is consistent with their observations, although there is additional scatter.
Taken at face value, the -0.15 dex/z trend found by Gallagher et al (2008) reduces in the intrinsic scatter in (MLCS2) SNIa Hubble diagrams from 0.18 mag to 0.14 mag.

This corresponds to a 9% systematic error in the dark energy equation of state parameter $w = P/(\rho c^2)$.
The NASA/DOE Joint Dark Energy Mission will (now) likely combine three mission concepts to measure the cosmic acceleration via white dwarf supernovae, weak lensing, and baryon acoustic oscillations.

The combined tighter parameter constraints may make it possible to distinguish “dark energy” from “modification of General Relativity” as an explanation for cosmic acceleration.
A focus of the (Destiny) SNla theory effort is reducing the scatter in SNla Hubble diagrams by elucidating systematic trends that can be tested.

We want to increase the homogeneity of the objects used as probes of the dark energy by finding observable signatures of different populations (e.g., single degenerate versus double degenerate).
The next decade will be an incredible time for SNIa research and probing the cosmic expansion history.

Lauer et al. 2008

Questions and Discussion