Theories for the Phillips Relation for Type Ia Supernovae

SNe Ia Data as a Cosmological Tool

SNe are bright \( E \sim 10^{51} \) erg, and we “know” their intrinsic luminosity. Can probe propagation of light from a SN to us

\[
d_L = \sqrt{\frac{L}{4\pi F}}
\]

\[
m(z) = M + 5 \log \left( \frac{d_L}{1 \text{ Mpc}} \right) + 25
\]

\[
d_L = \frac{c}{H_0 \sqrt{|\kappa_0|}} (1 + z) S_k \left( \sqrt{|\kappa_0|} \int_{z'=0}^{z} \mathrm{d}z' \frac{d(z')}{{\sqrt{\sum_i \Omega_i (1 + z')^3 (1 + w_i) - \kappa_0 (1 + z')^2}}} \right)
\]

\[\kappa_0 = \sum_i \Omega_i - 1\]

How much of what is in the Universe?
On the Luminosity of a SN Ia

Do we really know their intrinsic luminosity?

Range of values for $M_{\text{max}}$

NOT standard candles

But correlation with $\Delta m_{15}$

Standardizable candles

How well do we know this relation?

<table>
<thead>
<tr>
<th>BANDPASS</th>
<th>$a$</th>
<th>$b$</th>
<th>$\sigma$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>$-21.726(0.498)$</td>
<td>$2.698(0.359)$</td>
<td>$0.36$</td>
</tr>
<tr>
<td>V</td>
<td>$-20.883(0.417)$</td>
<td>$1.949(0.292)$</td>
<td>$0.28$</td>
</tr>
<tr>
<td>I</td>
<td>$-19.591(0.415)$</td>
<td>$1.076(0.273)$</td>
<td>$0.38$</td>
</tr>
</tbody>
</table>
Hubble Diagrams

Cosmological Constraints
Can We Understand the Phillips Relation?

Lots of Unknowns in a SN Ia Explosion

- Structure of the progenitor
- Precise ignition conditions
- Nuclear combustion physics

Do We Know “Enough?”

- SNe Ia from thermonuclear disruption of C-O WDs near Chandrasekhar limit
- Nuclear physics determines WDs’ structure.
- Explosion energy depends on binding energy of WD
- Light curves powered by radioactive decay $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$

Challenge

Theoretical explanation of why larger $M_{\text{Ni}}$ SNe Ia have broader B-band LCs

(Höflich 2006)
In a SN Ia, ejecta optically thick for months after explosion: width of bolometric light curve related to photon diffusion time $t_d$.

Assuming random walk,

$$ c t_d = N \lambda_p $$

$$ R^2 = \langle r^2 \rangle = N \lambda_p^2 $$

$$ t_d = \frac{R^2}{\lambda_p c} = R^2 \frac{\kappa \rho}{c} = \left( \phi_{Ni} vt \right)^2 \frac{\kappa \rho}{c} $$

$$ M \sim \rho (vt)^3 $$

$$ E_K \sim M v^2 $$

$$ t_d \sim \left( \frac{\kappa^2 M^3}{E_K} \right)^{1/4} $$

three variables
Increasing $\kappa$ with $M_{\text{Ni}}$

$\kappa$ dominated by $e^-$ scattering and bound-bound line transitions (enhanced by Doppler broadening in the differentially expanding ejecta)

Line opacity dominated by iron group species (complex atomic structure)
In particular, many short $\lambda$ lines: opacity increases sharply to the blue

Three proposed explanations:

- Larger $M_{\text{Ni}}$ leads to more heating and higher $T$ (H96)
  Radiation energy concentrated at shorter $\lambda$ leads to higher $\kappa$

- $t_d$ determined by rate at which short $\lambda$ photons fluoresce to longer $\lambda$ (PE01)
  Fluorescence more efficient in singly ionized species, i.e. in lower $M_{\text{Ni}}$ SNe Ia

- Larger $M_{\text{Ni}}$ leads to greater abundance of Fe group elements, i.e. higher $\kappa$ (M07)

These arguments all apply to bolometric LCs.
Woosley et al. explored grid of 130 1D models and extracted resulting LCs:

- Masses of $^{56}\text{Ni}$, stable iron, and IME (Si–Ca) are free parameters
- Explosion energy: uniform deposition corresponding to change in composition

[Diagram of the Phillips relation]
Input from 1D Models

Keeping only models compatible with Phillips relation:

Input from 1D Models

Very little dependence of the bolometric LCs on $M_{\text{Ni}}$:

<table>
<thead>
<tr>
<th>$M_{\text{Ni}}$</th>
<th>$t_{\text{bol}}$</th>
<th>$\Delta M_{15(\text{bol})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>15.56</td>
<td>0.81</td>
</tr>
<tr>
<td>0.63</td>
<td>15.55</td>
<td>0.82</td>
</tr>
<tr>
<td>0.56</td>
<td>15.54</td>
<td>0.83</td>
</tr>
<tr>
<td>0.49</td>
<td>15.56</td>
<td>0.84</td>
</tr>
<tr>
<td>0.42</td>
<td>15.52</td>
<td>0.84</td>
</tr>
<tr>
<td>0.35</td>
<td>15.51</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Alternative or complementary explanation needed

Input from 1D Models

Hint in the color evolution of the models:

- Little variation between models around $t_{B_{\text{max}}}$.
- Significant differences 15 days after $t_{B_{\text{max}}}$.
- Colors of dimmer (less massive) objects evolve faster.

Color Evolution and the Phillips Relation

Pre-maximum dimmer / redder relation

\[ T \propto L^{1/4} \propto (M_{\text{Ni}})^{1/4} \]

20% difference
(color difference less than 0.15 mag)

\( T \)-dependence of Fe II / Co II lines responsible for post-maximum evolution

Lines become prominent when \(^{56}\)Ni rich layers recombine to be singly ionized.

Abrupt transition at 7,000 K

Since higher \( M_{\text{Ni}} \) SNe Ia have higher \( T \), transition is delayed

Colors of dimmer (less massive) objects evolve faster.

Color Evolution and the Phillips Relation