Comparing Hydrodynamic Models with Observations of Type II Plateau Supernovae

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Outline

- Introduction
- Hydrodynamical Code
- Data Sample: Bolometric Corrections
- Analysis of our Sample of SNe II-P
Supernovae

- **Kinetic energy:** $\sim 10^{51}$ erg = 1 foe = 1 B
- **Radiated energy:** 1-10% $E_k$ during weeks/months ($\sim 10^{10} L_\odot$)
- **Velocities:** $v_{\text{exp}} \sim 10^4$ km s$^{-1}$ $\Rightarrow \sim 10^5 R_\odot$ (few weeks)
- **Temperature:** $\sim T_\odot$ $\Rightarrow R = (L/L_\odot)^{1/2} R_\odot \sim 10^5 R_\odot$ (few weeks)

CSP supernovae  
SN 1987A
Supernova Classification

thermonuclear

\[ \text{Ia} \xrightarrow{\text{yes}} \text{Ia} \] \[ \text{SiII} \xrightarrow{\text{no}} \text{HeI} \xrightarrow{\text{yes}} \text{Ib} \xrightarrow{\text{no}} \text{Ic} \xrightarrow{\text{no}} \text{Ib/c pec} \xrightarrow{\text{yes}} \text{IIn} \]

core collapse

\[ \text{H} \xrightarrow{\text{yes}} \text{IIb} \xrightarrow{\text{dashed}} \text{IIL} \xrightarrow{\text{light curve shape}} \text{IIP} \]

\[ \text{II} \]

\[ \text{I} \]

Turatto (2003)
Type II-P Supernovae

- **Spectroscopy**: prominent P-Cygni Balmer lines
- **Photometry**: long plateau phase (L $\sim$ const. for $\sim$100 days)
- **Spectropolarimetry**: explosion approximately spherical
- Most common type of SN (59% of CCSNe)

![Graph showing spectral lines and light curve](image-url)
Type II-P Supernovae

- Good distance indicators
  - Expanding photospheric method (EPM)
  - Spectral fitting expanding atmosphere method (SEAM)
  - Standard candle method (SCM)

- Connection with final stages of stellar evolution

  Physical properties of the progenitor
SN II-P Progenitors

- Wide range of plateau luminosity ($L_p$), plateau durations ($\Delta t_p$) and expansion velocities ($v_p$) $\implies$ Different progenitors properties
- Light curve + spectral modelling $\implies M_{ej}$, $R$, $E_{exp}$ and $M_{Ni}$
- Pre-supernova imaging + stellar evolution models $\implies M_{ZAMS}$

Litvinova & Nadezhin 1983

Smartt et al. 2009
Type II-P Supernovae

- Good distance indicators: EPM, SEAM and SCM
- Connection with final stages of stellar evolution

Physical properties of the progenitor:

- Red supergiant structure with H-rich envelope (Van Dyk et al. 2003)
- Stellar evolution: $M_{\text{ZAMS}}$: 8 – 25 $M_\odot$ (Heger et al. 2007)
- Pre-SN imaging: $M_{\text{ZAMS}}$: 8 – 17 $M_\odot$ (Smartt et al. 2009)
- Hydrodynamical modelling favors high mass range (Utrobin & Chugai 2008)

- Availability of a large of SN II-P
Sample of SNe II-P

- ∼30 nearby SNe II-P: Calán/Tololo, SOIRS and CATS (1986-2003)
- High-quality, well-sampled $BVRI$ light curves and spectra
- The CSP is providing even more objects (∼ 80 SNe II-P)
Type II-P Supernovae

- Good distance indicators: EPM, SEAM and SCM

- Connection with final stages of stellar evolution

  Physical properties of the progenitor:

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  - Hydrodynamical modelling favors high mass range
    (Utrobin & Chugai 2008)

- Availability of a large data of SN II-P

- Development of our own code to compare with our database of SNe II-P
Theoretical model of LC $\implies$ numerical integration of the hydrodynamic equations $+$ radiative transfer

Assumptions:

- Spherically symmetric explosion $\implies$ One-dimensional code
- Diffusion approximation with flux-limited prescription
- Computation of shock wave using an *artificial viscosity* term
- Explosion simulated by a sudden release of energy near the core
- Energy released by radioactive decay
\[ V = \frac{4\pi}{3} \frac{\partial r^3}{\partial m} \]  
\[ \frac{\partial r}{\partial t} = u \]  
\[ \frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial}{\partial m} (P + q) - \frac{Gm}{r^2} \]  
\[ \frac{\partial E}{\partial t} = \epsilon_{Ni} - \frac{\partial L}{\partial m} - (P + q) \frac{\partial V}{\partial t} \]  
\[ L = -\left(4\pi r^2\right)^2 \frac{\lambda ac}{3\kappa} \frac{\partial T^4}{\partial m} \]

\[ \Rightarrow \text{Mass conservation} \]
\[ \Rightarrow \text{Velocity} \]
\[ \Rightarrow \text{Momentum conservation} \]
\[ \Rightarrow \text{Energy conservation} \]
\[ \Rightarrow \text{Radiative energy transport} \]

Initial and boundary conditions, and constituent equations
Method of finite differences: space-time grid

Explicit scheme for the hydrodynamics ($\Delta t \leq t_{\text{Courant}}$) and implicit for the temperature

Gamma-ray deposition from $^{56}\text{Ni} - ^{56}\text{Co} - ^{56}\text{Fe}$ decay

Transfer equation in grey approximation: $\frac{dI}{d\tau} = -I + S$

Arbitrary spherically symmetric distribution of $^{56}\text{Ni}$

$\frac{dE}{dm} = \kappa_\gamma \int I d\Omega$; $\kappa_\gamma = 0.03$ cm$^2$ g$^{-1}$
Initial models

- Polytropic models: single and double
- Evolutionary calculations
Initial models

- Polytropic models: single and double
- Evolutionary calculations

Double Polytrope

![Graph showing double polytrope](image-url)
Initial models

- Polytropic models: single and double
- Evolutionary calculations

Evolutionary models

![Graph showing evolutionary models with different models represented by different colors and markers.](SNII-P Light Curves -- p.14/39)
RESULTS
Theoretical Bolometric LC

- Model with $E = 1.3$ foes, $R_0 = 800 \, R_\odot$, $M_0 = 19 \, M_\odot$

Evolutionary phases

![Graph showing light curve with key markers: shock breakout, plateau, transition, radioactive decay.](image-url)
Before breakout

Model with $E = 1.3$ foes, $R_0 = 800 \, R_\odot$, $M_0 = 19 \, M_\odot$
Before breakout

Model with $E = 1.3$ foes, $R_0 = 800 \ R_\odot$, $M_0 = 19 \ M_\odot$
After breakout

Model with $E = 1.3$ foes, $R_0 = 800 \, R_\odot$, $M_0 = 19 \, M_\odot$

Profiles of the fraction of ionized Hydrogen

![Graph showing profiles of the fraction of ionized Hydrogen over time and mass.]
After breakout

Model with $E = 1.3$ foes, $R_0 = 800 \, R_{\odot}$, $M_0 = 19 \, M_{\odot}$

Temperature profiles
Variation of Parameters
Variation of Parameters

Light curves for different energies

![Graph showing light curves for different energies](image-url)
Variation of Parameters

Light curves for different radii

![Graph showing light curves for different radii]
Variation of Parameters

Light curves for different masses

![Graph showing light curves for different masses with logarithmic scale for luminosity and linear scale for time. The graph includes curves labeled with masses of 14, 18, and 22 solar masses.](image-url)
Variation of Parameters

Light curves for different $^{56}$Ni mass

![Graph showing light curves for different $^{56}$Ni mass]
Variation of Parameters

Light curves for different $^{56}\text{Ni}$ distribution

![Graph showing light curves for different $^{56}\text{Ni}$ distribution](image-url)
DATA SAMPLE
Bolometric Correction
Bolometric Correction

- Three well-observed supernovae: SN 1987A, SN 1999em, and SN 2003hn
- Integration of all the available broadband data
- Estimation of the missing flux in UV and IR: blackbody (BB) fit
- Calculation of BC for two atmosphere models: Eastman et al. (1996) and Dessart & Hillier (2005)
Bolometric Correction

\[ BC = m_{bol} - [V - A_V], \quad rms = 0.11 \text{ mag} \]
Sample of SNe II-P

Calculation of bolometric LCs for our sample of SNe II-P

$$\log L [\text{erg s}^{-1}] = -0.4 \left[ BC(\text{color}) + V - A_{\text{total}}(V) - 11.64 \right] + \log(4 \pi D^2)$$

Olivares et. al (2010): $D, A_{\text{host}}(V)$
Sample of SNe II-P

- Calculation of bolometric LCs for our sample of SNe II-P
- Estimation of parameters to characterize the LCs:
  - $L_p$: plateau luminosity
  - $\Delta t_p$: plateau duration
  - $\Delta \log L$: luminosity drop
  - $M_{\text{Ni}}$: $^{56}\text{Ni}$ mass

- Analysis of observed parameters
Slope during Plateau

- Bi-modal tendency
- \( \text{slope} > -1 \text{ mag/100 d} \rightarrow \text{“normal plateau”} \)
- \( \text{slope} < -1.25 \text{ mag/100 d} \rightarrow \text{“intermediate-plateau”} \)
Bolometric Luminosity Range

- Weighted average $\langle L_p \rangle = 1.26 \times 10^{42}$ erg s$^{-1}$
- Range of 1.15 dex in $L_p$
\textbf{\textsuperscript{56}Ni mass}

- $M_{\text{Ni}}$ sensitive to adopted explosion time
- Assumed local deposition of gamma rays
- Weighted average $\langle M_{\text{Ni}} \rangle = 0.024 M_\odot$
- $M_{\text{Ni}} < 0.1 M_\odot$, except for SN 1992am ($M_{\text{Ni}} > 0.26 M_\odot$)
Model vs. Observation
Hydro-Model of SN 1999em

- Proto-type SN II-P
- One of the best-observed SNe II-P
- Determination of physical parameters ($M_0, R_0, E$ and $M_{Ni}$) by comparing
  - bolometric light curve
  - photospheric velocity evolution
Hydro-Model of SN 1999em

- Extended $^{56}\text{Ni}$ mixing
- Very good agreement with observations
- Physical parameters similar to previous hydrodynamical studies (Baklanov et al. 2005; Utrobin 2007)
- Low-mass models are not favored

Bersten, Benvenuto & Hamuy, ApJ in press
Grid of Hydrodynamical Models

Set of 46 hydrodynamical models:

- $M_0 = 10, 15, 20$ and $25 \, M_\odot$
- $E = 0.5, 1, 2$ and $3 \, \text{f.o.e}$
- $R_0 = 500, 1000$, and $1500 \, R_\odot$
- $M_{Ni} = 0.02, 0.04$ and $0.07 \, M_\odot$

For each model: $L_p, \Delta t_p, \Delta L, M_{Ni}$ and $v_{-30}$ are measured consistently with observations.

- Dependence of observable parameters on physical quantities
- Study of correlations between observable parameters
Model dependences

- Symbols: size proportional to $M_0$, shape indicates different $R_0$ and colors related with $M_{Ni}$ (fixed mixing)

- Plateau luminosity

- Strong correlation with explosion energy

- $\sim 0.4$ dex of dispersion mainly related to $M_0$ and $R_0$

- $M_{Ni}$ (fixed mixing) is not very influential
Model dependences

Symbols: size proportional to $M_0$, shape indicates different $R_0$ and colors related with $M_{Ni}$ (fixed mixing)

Plateau duration

- Weaker correlation with explosion energy
- $M_0$ seems the most important factor but $M_{Ni}$ also produces an effect
- $R_0$ produces a minor effect
Observed and Modeled Correlations

The Standard Candle Method (SCM):

- Correlation between luminosity and expansion velocity during the plateau phase found by Hamuy & Pinto (2002)

- Detailed study of this correlation for our sample of SNe II-P given by Olivares et al. (2010) leading to a precision of 13% in distance

- Study of this correlation using our hydrodynamical models
Observed and Modeled Correlations

- **Symbol Colors**: different explosion energies ($E$)

- Models reproduce very well the observed trend

- $E$ is the main driver

- Shift between models and observations
Observed and Modeled Correlations

Symbol Colors: different explosion energies \( (E) \)

Shift between models and observations:

- Adopted \( H_0 \)
- Extinction correction
- Measurement inconsistencies
- High-mass models

![Graph showing SCM relations with symbols for models and observations](image-url)
Observed and Modeled Correlations

- **Symbol Colors:** different explosion energies ($E$)

- Models show slight correlation previously noted by Kasen & Woosley (2009)

- Observations show no correlation

- Lowest $E$ and high $M$ are not favored
Grid hydro Models using pre-SN models from stellar evolutionary calculations: \(E=0.5-4\) foe, \(M= 10.9-15.8\ M_\odot\) and \(R= 625-1349\ R_\odot\)

**Strong correlation**

\[ M_{V,50} = -18.4 - 0.03[t_p,0 - 100] \]

**Correction by \(^{56}\)Ni mass is needed**

\[ t_p = t_{p,0} \times \left(1 + 0.35M_{ni}E_{51}^{-1/2}R_0^{-1}M_{ej}^{1/2}\right)^{1/6} \]
Observed and Modeled Correlations

- **Symbol Colors:** different explosion energies ($E$)

- Models show slight correlation previously noted by Kasen & Woosley (2009)

- Observations show no correlation

- Lowest $E$ and high $M$ are not favored
Summary

We implemented a robust method to estimate BC from $BVI$ photometry for SNe II-P with typical scatter of $\sim 0.1$ mag.

We studied SN 1999em in detail obtaining a very good agreement with observations when extended mixing of $^{56}$Ni is used.

We calculated a set of observable parameters ($L_p$, $\Delta t_p$, $\Delta L$ and $M_{Ni}$) for our data sample and for a grid of hydrodynamical models:

- Parameter distribution:
  - Bi-modal tendency of the slope during plateau
  - 1.15-dex range in plateau luminosities
  - $M_{Ni} < 0.1M_\odot$, except for SN 1992am with $M_{Ni} > 0.26M_\odot$

- Dependence on physical quantities ($E$, $R_0$, $M_0$ and $M_{Ni}$)

- Correlations using models and observations
  - Models confirm the SCM relation
  - Lowest $E$ and high $M$ are not favored
Plateau Lengths

- Weighted average $\langle \Delta t_p \rangle = 90.47$ days
- Most SNe with $\langle \Delta t_p \rangle$ between 75 and 105 days
- Bi-modal trend in the distribution (secondary peak at $\sim 60$ days)
Luminosity drop: $\Delta \log L$

- Weighted average $\langle \Delta \log L \rangle = 0.783$ dex
- Range of 0.35–1.46 dex in $\Delta \log L$
Model dependences

Symbols: size proportional to $M_0$, shape indicates different $R_0$ and colors related with $M_{Ni}$ (fixed mixing)

- Luminosity drop

- Some dependence on explosion energy

- Strong correlation with $M_{Ni}$

- Some dependence on $R_0$ but not on $M_0$
Model dependences

- Symbols: size proportional to $M_0$, shape indicates different $R_0$ and colors related with $M_{Ni}$ (fixed mixing)

- Strong correlation with explosion energy

- $M_0$ is the main driver of the dispersion

- Slight dependence on $M_{Ni}$ but not on $R_0$

Expansion velocity

![Graph showing correlation between $E$ and $\log v_{30}$]
Observed and Modeled Correlations

Symbol Colors: different explosion energies ($E$)

- No correlation
- Ni mass affects tail luminosity but not the plateau
Comparison with STELLA Code

STELLA code (Blinnikov et al. 1998):
- implicit hydrodynamics + multi-group radiative transfer
- includes the effect of the line opacities

STELLA calculations by N. Tominaga