Constraining massive star activities in the final years through properties of supernovae and their progenitors

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Enhanced mass loss shortly before supernova explosion

Some massive stars experience the enhanced mass loss ($>10^{-4} \, M_{\text{sun}}/\text{yr}$) shortly ($\text{yr} - \text{decades}$) before supernova ($r < 10^{15} \, \text{cm}$).

- Observational evidence
  - SNe IIn, Ibn (Taddia et al. 2013)
  - Progenitor variability (Mauerhan et al. 2013)
  - Flash spectroscopy (Yaron et al. 2017)
  - Modeling early time light curve (Förster et al. 2018)

The typical value for stellar wind

\[
\log \dot{M} (M_{\odot} \, \text{yr}^{-1}) = 10^{-3} \, \text{M}_{\odot} \, \text{yr}^{-1}
\]

(Förster et al. 2018)

\[
\rho (\text{g cm}^{-3}) = 10^{-22} - 10^{-10}
\]

(Yaron et al. 2017)

\[
\text{Radius (cm)} = 10^{14} - 10^{16}
\]
Energy deposition into the envelope may causes mass loss

- Gravity waves (Quataert & Shiode 2012, Fuller 2017).
  - Gravity waves are excited by core convection
    => Propagate to the envelope as a pressure waves
    => Energy is deposited into the envelope
    => Mass loss ?

- Binary interaction (Chevalier 2012)

- Instabilities in the convective burning shells
  (Arnett & Meakin 2011)

Super-Eddington energy injection occurs only for the last ~ yr before the SN
Energy deposition into the envelope causes mass loss?

- Gravity waves (gravity waves, Quataert & Shiode 2012).
- Binary interaction (Chevalier 2012)
- Instabilities in the convective burning shells (Arnett & Meakin 2011)
The aim and conclusion of our research

Aim

Investigate the effect of **pre-SN energy injection into the envelope** on the progenitor’s structure and supernovae.

· Can it explain the confined CSM inferred for SNe II?

· What kind of energy injection is allowed in order to be consistent with the observational data set
The aim and conclusion of our research

Investigate the effect of **pre-SN energy injection into the envelope** on the progenitor’s structure and supernovae.

- Can it explain the confined CSM inferred for SNeII?

- What kind of energy injection is allowed in order to be consistent with the observational data set

**Conclusion**

- It is difficult to reproduce the confined CSM inferred from observations.

- The pre-SN energy injection rate should be at most one order of magnitude higher than the Eddington luminosity.
Calculation procedure

Pre-MS $\rightarrow$ **3.0 yrs** before SN $\rightarrow$ SN

- Hydrostatic
- Hydrodynamic

M$_{\text{ZAMS}}$=15Msun

Energy injection at a constant rate

- Light curve
- Expansion velocity, etc

MESA (Paxton et al. 2011)
: One-dimensionnal stellar evolution code

SNEC (Morozova et al. 2015)
: One-dimensionnal RHD code
Calculation procedure

Pre-MS  $3.0 \text{ yrs}$ before SN  SN

Hydrostatic  Hydrodynamic

Energy injection at a constant rate

$M_{\text{ZAMS}} = 15 \text{Msun}$

- Light curve
- Expansion velocity, etc

- Injection rate $L_{\text{dep}}$:
  $10^{38}, 10^{39}, 5.0 \times 10^{39}, 10^{40} \text{ erg/s}$

- Location of energy deposition
  - Uniformly into the envelope (UNIFORM)
  - Base at the hydrogen envelope with the width of $0.1M_{\text{sun}}$ (BASE)
  - Around the middle of the envelope with gaussian (MIDDLE)

$\epsilon_{\text{inject}} \propto \frac{L_{\text{dep}}}{\sigma \sqrt{2\pi}} \exp \left( -\frac{(r - r_{\text{dep}})^2}{2\sigma^2} \right)$  \hspace{1cm} (r_{\text{dep}} = 500R_{\text{sun}})
Density profile of the progenitor at the time of core collapse

- \( L_{\text{dep}} = 5.0 \times 10^{39} \text{ erg/s}, \text{ UNIFORM} \)

- It expands to \( \sim \) a few \( \times 10^{14} \text{cm} \)
  → Consistent with Yaron et al. 2017

- CSM density is orders of magnitudes higher than inferred from the observations
  (i.e. \( \sim 10^{-3} \, M_\odot \text{yr}^{-1} \); Yaron et al. 2017, Forster et al. 2018)
Light curves of the supernova

- $L_{\text{dep}} = 5.0 \times 10^{39} \text{ erg/s, UNIFORM}$

- **Bolometric**
  - Plateau is **brighter** and **longer**

- **V-band**

→ Both bolometric and V-band light curve do not match with observations.

Data for SNe II

Without pre-SN energy injection

$L_{\text{dep}}=5.0\times10^{39} \text{ erg/s, Uniform}$
Photospheric velocity of supernova

- $L_{\text{dep}} = 5.0 \times 10^{39} \text{ erg/s, UNIFORM}$

- Almost constant until $\sim 50$ days.
  \[ \rightarrow \text{Inconsistent with observations.} \]

- Larger initial progenitor radius
  \[ \rightarrow \text{Adiabatic cooling is inefficient} \]

- Hydrogen recombines later ($t > 50$ days)

Without pre-SN energy injection

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Photospheric velocity of supernova

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(Takats & Vinko 2012)
Time evolution of photospheric temperature

- Photospheric velocity

Without pre-SN energy injection

\[ L_{\text{dep}} = 5.0 \times 10^{39} \text{ erg s}^{-1}, \text{ UNIFORM} \]

No energy injection

SN 1999em
SN 2004dj
SN 2004et
SN 2005cs
SN 2006bp
SN 2009N
SN 2012A

Recombination temperature

With the pre-SN energy injection

\[ \rightarrow \text{ temperature evolve more slowly.} \]
The dependence on the energy injection locations

- $L_{\text{dep}} = 5.0 \times 10^{39}$ erg/s

\[ \dot{M} = 10^{-3} M_\odot \text{ yr}^{-1} \]

- Bolometric luminosity (erg s$^{-1}$)
- Photospheric velocity (km s$^{-1}$)
- Time since the shock breakout (day)
The dependence on the energy injection locations

- \( L_{\text{dep}} = 5.0 \times 10^{39} \text{ erg/s} \)

The progenitor density structure is quite different. But, \( L_{\text{bol}} \) and \( V_{\text{ph}} \) of SN behaves similarly.
The dependence on the energy injection rates: $L_{\text{dep}}$
The dependence on the energy injection rates: $\mathbf{L_{\text{dep}}}$

**Eddington luminosity $L_{\text{EDD}}$:**

$$L_{\text{EDD}} \equiv \frac{4\pi G c m}{\kappa} \approx 10^{38}\text{ ergs}^{-1}$$

- $L_{\text{dep}} \lesssim L_{\text{EDD}} \rightarrow$ Expands modestly ($<10^{14}\text{ cm}$)
  - Minor effect on SN
- $L_{\text{dep}} >> L_{\text{EDD}} \rightarrow$ Expands significantly ($>10^{14}\text{ cm}$)
  - Significant effect on SN
  - **Inconsistent with observations**
The evolution of a progenitor on the HR diagram

- Different injection locations
- Different injection rates

(Smartt 2015)
The evolution of a progenitor on the HR diagram

- **Different injection locations**
  - UNIFORM
  - BASE
  - MIDDLE
  - Within 1 yr before core collapse
  - Within 3 yrs before core collapse

- **Different injection rates**
  - \( L_{\text{dep}} = 10^{39} \text{ erg/s} \)
  - \( L_{\text{dep}} = 5.0 \times 10^{39} \text{ erg/s} \)
  - \( L_{\text{dep}} = 10^{40} \text{ erg/s} \)

If \( L_{\text{dep}} \gg L_{\text{EDD}} \), the location of progenitor becomes **inconsistent** with the detected progenitors.
Discussion: Secondary effects caused by envelope inflation?

- It is difficult to **directly** produce the confined CSM by the energy injection.
  - \( L_{\text{dep}} \gg L_{\text{EDD}} \rightarrow \text{Inconsistent with observations} 
  - \( L_{\text{dep}} \leq L_{\text{EDD}} \rightarrow \text{Expands only modestly (<10^{14} \text{ cm})} 

\[ \Rightarrow \text{A secondary effects by sub-Eddington energ injection likely induces the mass loss.} \]
  - Stellar pulsation.
  - Binary interaction, etc.

\[ L_{\text{dep}} = 10^{38} \text{ erg/s, UNIFORM} \]

No energy injection

Energy injection
\[ \rightarrow \text{Pulsation growth rate gets larger.} \]
Discussion: Possible application to peculiar objects

- **SN IIP 2009kf**: Unusually bright plateau (Boticella et al. 2010)

  => Extremely high (~$2 \times 10^{52}$ erg) explosion energy? (Utrobin et al. 2010)

- **Our models can explain it without assuming unusually high energy.**

- **Model:** $L_{\text{dep}} = 2.5 \times 10^{39}$ erg/s, UNIFORM ($E_{\text{exp}} = 2.8 \times 10^{51}$ erg) (Ouchi et al., in prep)
Summary

• We have investigated the effect of pre-SN energy deposition on the progenitors and SNe.

• Highly super-Eddington energy injection should not take place for the last few years for typical SNe II progenitors.

• With sub-Eddington energy injection, it is difficult to produce the extended CSM (>10^{14} \text{ cm}) within a few years.

• A secondary effect triggered by sub-Eddington energy injection (e.g. pulsation, binary interaction) likely induces the pre-SN mass loss.