The Surprisingly Dynamic Last Years in the Lives of Massive Stars

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Fig. 1. The luminosity evolution (light curve) of supernovae. Common SN explosions reach peak luminosities of \(10^{51} \text{ ergs s}^{-1} \) (absolute magnitude \( > -19.5 \)). Superluminous SNe (SLSNe) reach luminosities that are greater by a factor of \( \sim 10 \). The prototypical events of the three SLSN classes—SLSN-I [PTF09kd (90)], SLSN-II [SN 2006gy (12, 13, 77)], and SLSN-R [SN 2007bi (77)]—are compared with a normal type II SN (Nugent template), the type Ib SN 2005dc (89), the average type Ib light curve from 65s, the type Ib SN 2011dh (28), and the prototypical type I-P SN 1999em (79). All data are in the observed R band at 680.
Outline

• Observational Evidence for Extreme Mass Loss in the Last Few Years of the Lives of Massive Stars

• Late Stages of Massive Stellar Evolution

• Energy & Angular Momentum Transport by Convectively Excited Waves
  • Implications for Mass Loss & the Spins of Compact Objects
Core Collapse SNe

SNe II

- II-P: 70%
- II-L: 10%
- IIb: 12%
- II-n: 9%

Li+2011 (LOSS)
Supernovae Powered by Interaction with Ambient Gas (Type IIn SNe)

- Interacting SNe: SN shock runs into dense wind at $\sim 10^{2-3}$ AU and KE $\Rightarrow$ thermal energy, radiation

Analogous to supernova remnant but interaction is much closer to the star with stellar wind not ISM
Supernovae Powered by Interaction with Ambient Gas (Type IIin SNe)

- Interacting SNe: SN shock runs into dense wind at $\sim 10^{2-3}$ AU and KE $\Rightarrow$ thermal energy, radiation

$$\tau_{diff} \sim \frac{R^2}{\ell_{mfp} c} \sim \tau_{exp} \sim \frac{R}{v_{sh}}$$

$$R \sim \left( \frac{M \kappa v_{sh}}{4c} \right)^{1/2} \sim 100 \text{ AU}$$

$R \sim 10^{2-3}$ AU optimal for converting KE of shocked wind $\Rightarrow$ radiation
Supernovae Powered by Interaction with Ambient Gas (Type IIn SNe)

- Interacting SNe: SN shock runs into dense wind at $\sim 10^{2-3}$ AU and KE $\Rightarrow$ thermal energy, radiation

- $v_{\text{wind}} \sim 10^3$ km/s & $R \sim 10^{2-3}$ AU $\Rightarrow$ interaction with mass lost in last $\sim$ years of stellar evolution

- Unique probe of massive stars just prior to core collapse
Pre SN Mass Loss Rate Can be Estimated From Observations

Radiative Shocks

\[ L \sim \rho_{\text{wind}} v_{\text{sh}}^3 \]
\[ \sim M_{\text{wind}} v_{\text{sh}}^2 / (R/v_{\text{sh}}) \]

Figure 13. Decomposition of the H\(\alpha\) feature in the 2005 April 30 spectrum of SN 2005bx.
Pre SN Mass Loss Rate Can be Estimated From Observations
Superluminous SNe can have $E_{\text{radiated}} \approx 10^{51}$ ergs $\approx E_{\text{kinetic}}$

one type is interaction with particularly large mass ejection $\approx M_{\odot}$ prior to core collapse

**Fig. 1.** The luminosity evolution (light curve) of supernovae. Common SN explosions reach peak luminosities of $\approx 10^{43}$ erg s$^{-1}$ (absolute magnitude $> -19.5$). Superluminous SNe (SLSNe) reach luminosities that are greater by a factor of $\approx 10$. The prototypical events of the three SLSN classes—SLSN-I [PTF09cnd (4)], SLSN-II [SN 2006gy (12, 13, 77)], and SLSN-R [SN 2007bi (7)]—are compared with a normal type Ia SN (Nugent template), the type IIn SN 2005cl (56), the average type Ib/c light curve from (65), the type IIb SN 2011dh (78), and the prototypical type II-P SN 1999em (79). All data are in the observed $R$ band (80).
Shock Breakout in a Wind

Large $\dot{M}_{\text{wind}}$ prolongs shock breakout signature

Ofek+2010 infer $\dot{M}_{\text{wind}} \sim 0.1 \, M_\odot \, \text{yr}^{-1}$
Pre-SN Outbursts

50L_{\text{Edd}} for 50M_\odot star

$0.1M_\odot N_{\text{I}}^{56} + C_{\text{O}}^{56}$
My foray into sophisticated data science

- $\Delta M$ up to $\sim M_{\text{sun}} \Rightarrow \Delta M/M \sim 10^{-4} - 10^{-2}$
- $\Delta t \sim \text{yrs} \Rightarrow \Delta t/t_{\text{lifetime}} \sim 10^{-7}$
- Large $\dot{M}$ inferred in few % of SNe $\Rightarrow$
  (though super-luminous SNe are rarer $\sim 10^{-4}$ SN rate)
- Suggests something unusual physically connected to late stages of massive stellar evolution
Thermal Balance in Stars

- Main sequence & low mass stellar evolution
  \[ L_{\text{fusion}} \sim L_{\text{rad}} + L_{\text{conv}} \]

- Late Stages of Massive Stellar Evolution
  - Temp for C fusion $\rightarrow$ thermal neutrino cooling important
  \[ L_{\text{fusion}} \sim L_{\text{neutrino}} \]
WOOSLEY, HEGER, AND WEAVER: EVOLUTION AND EXPLOSION OF MASSIVE STARS

\[ L_{\text{Oxygen}} \sim 10^4 L_{\text{Carbon}} \]
Thermal Balance in Stars

- Main sequence & low mass stellar evolution
  \[ L_{\text{fusion}} \sim L_{\text{rad}} + L_{\text{conv}} \]

- Late Stages of Massive Stellar Evolution
  - Temp for C fusion $\rightarrow$ thermal neutrino cooling important
  \[ L_{\text{fusion}} \sim L_{\text{neutrino}} \gg L_{\text{Edd}} \]
  - large $L_{\text{fusion}}$ accelerates stellar evolution
## Late Stages of Massive Stellar Evolution

### 25 $M_{\text{sun}}$ (MS lifetime $\sim 10^7$ yrs)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Duration ($t_{\text{nuc}}$)</th>
<th>$L_{\text{fusion}}$ ($L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>$\sim 10^3$ yr</td>
<td>$\sim 10^6$</td>
</tr>
<tr>
<td>Neon</td>
<td>$\sim 1$ yr</td>
<td>$\sim 10^9$</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$\sim 1$ yr</td>
<td>$\sim 10^{10}$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$\sim 1$ d</td>
<td>$\sim 10^{12}$</td>
</tr>
</tbody>
</table>

Late stage mass loss tied to C, Ne, O, & Si fusion stages of stellar evolution.
Preferential Mass Loss in the Years Prior to Core Collapse

- Binaries. e.g., Common Envelope Evolution with BH/NS that Ejects Mass & triggers Core Collapse (Chevalier 2012)

- Tap into Core Fusion Energy to Power Outflow
  - wave-driven mass loss (Quataert & Shioe 2012)
\( L_{\text{fusion}} \gg L_{\text{Edd}} \) in last \( \sim \) years

\( L_{\text{fusion}} \neq L_v \) everywhere \( \Rightarrow \) convection w/ \( L_{\text{conv}} \gg L_{\text{Edd}} \)
Convective Excitation of Waves

Radiative zone with waves excited by convection

Convection zone
Convective Excitation of Waves

Internal Gravity Waves

\[ \mathcal{M} = \frac{v_c}{c_s} \quad \text{(conv. Mach #)} \]

\[ \dot{E}_{\text{waves}} \gtrapprox \mathcal{M} L_{\text{conv}} \]

\[ \omega \sim \frac{v_c}{H} \]
Core Oxygen Fusion (~ yr) becomes outgoing sound waves in stellar envelope.

- $L_{\text{fusion}} \approx 10^{10} \, L_\odot$
- $L_{\text{wave}} \approx 10^{7.5} \, L_\odot$
- $\approx 100 \, L_{\text{edd}}$
- $\Delta E_{\text{fusion}} \approx 10^{51} \, \text{ergs}$
- $\Delta E_{\text{waves}} \approx 10^{48} \, \text{ergs}$
MESA Models with Super-Eddington Energy Deposition in Stellar Envelope

Star Expands to Become RSG

Mass Loss: $L_{\text{wave}} > L_{\text{Edd}}$

Binary: Roche Lobe Overflow
Core Oxygen Fusion (~ yr)

Outgoing gravity waves

Tunnel through evanescent zone

Become outgoing sound waves in stellar envelope

\[ L_{\text{photon}} \sim 10^5 \, L_\odot \]
\[ L_{\text{fusion}} \sim 10^{10} \, L_\odot \]
\[ L_{\text{wave}} \sim 10^{7.5} \, L_\odot \]
\[ \sim 100 \, L_{\text{EDD}} \]
\[ \Delta E_{\text{fusion}} \sim 10^{51} \, \text{ergs} \]
\[ \Delta E_{\text{waves}} \sim 10^{48} \, \text{ergs} \]

\[ \Delta M \sim M_\odot \left( \frac{v_{\text{wind}}}{300 \, \text{km s}^{-1}} \right)^{-2} \]
Variation in Wave-Driven Mass Loss with Progenitor
Variation in Wave-Driven Mass Loss with Progenitor

Star Expands to Become Giant w/ large $\dot{M}_{\text{wave}}$

($\dot{E}_{\text{wave}}$ deposited out in envelope)

$\sim 10\%$ of progenitors susceptible to wave $\dot{M}$

Large $\dot{E}_{\text{wave}}$ has little effect

($\dot{E}_{\text{wave}}$ deposited deep in star)
Core Fusion: Waves Propagate into Envelope
Shell Fusion: Waves Propagate into Envelope & Core
Effect of Waves on the Spin of the Stellar Core

(Fuller + 2015)

Internal Gravity Waves

\[ \dot{J} = \frac{m \dot{E}}{\omega} \]

\( \mathbf{J}_{\text{NS}} \sim 10^{47} (P/0.1\text{ s})^{-1} \text{ g cm}^2 \text{ s} \)

\( \mathbf{J}_{\text{waves}} \sim 3 \times 10^{49} \text{ g cm}^2 \text{ s} \)

\( \sim 3 \times 10^{48} \text{ g cm}^2 \text{ s} \)

Waves Can Dramatically Modify Spin of the Resulting NS

gravity waves travel into the core that will become a NS!

Shell C, O, Ne, Si Fusion

(~10 yr to ~ day)
What if the Fe Core is Very Slowly Rotating Prior to Core Collapse?

Core is Stochastically Spun Up by Waves from Si Shell Fusion

\[ J_{\text{core}} \sim \frac{J_{\text{waves}}}{N_{\text{eddy}}^{1/2}} \sim \frac{J_{\text{waves}}}{(\omega_c T_{\text{shell}})^{1/2}} \]

\[ N_{\text{eddy}} \sim 300 \text{ (Si shell fusion)} \]

(cf. \( N_{\text{eddy}} \sim 10^{11} \) for MS solar convection)
What if the Fe Core is Very Slowly Rotating Prior to Core Collapse?

Core is Stochastically Spun Up by Waves from Si Shell Fusion

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\[ N_{\text{eddy}} \sim 300 \ (\text{Si shell fusion}) \]

(cf. \( N_{\text{eddy}} \sim 10^{11} \) for MS solar convection)

\[ \Rightarrow P_{\text{NS}} \sim 0.1 \ \text{sec} \]

\( \sim \) estimated NS spin periods from population studies
Overview

- $L_{\text{fusion}} \gg L_{\text{Edd}}$ in last ~ yr-decade of stellar evolution $\rightarrow$ vigorous convection and a super-Eddington wave flux

- prodigious mass loss seen in circumstellar interaction and shock breakout from core-collapse SNe

- reshapes the spin of the stellar core & plausibly explains the typical ~0.1 sec spin of radio pulsars

**SNe II**

- IIb: 12%
- II-L: 10%
- II-P: 70%
- IIn: 9%

**P-Pdot Diagram**

- SGRs, AXPs
- Radio Pulsars

Fig. 1. The luminosity evolution light curve of supernovae. Common SN explosions reach peak luminosities of $\sim 10^{44}$ ergs s$^{-1}$, absolute magnitude $\sim -19.5$. Superluminous SNe (SLSNe) reach luminosities that are greater by a factor of $\sim 10$. The prototypical events of the three SLSN classes—SLSN-i (PTF12kht, G), SLSN-II (SN 2011fe, G2, 3J, 707), and SLSN-IR (SN 2007bi, H)—are compared with a normal type IIa SN (SN1987A, template), the type Ib SN 2005dc (G), the average type Ib light curve from Della, the type Ib SN 2011fe (R), and the prototypical type Ia SN 1991bg. All data are in the observed $R$ band (600).