The features of multiple mass eruptions from progenitors of Type IIn supernovae

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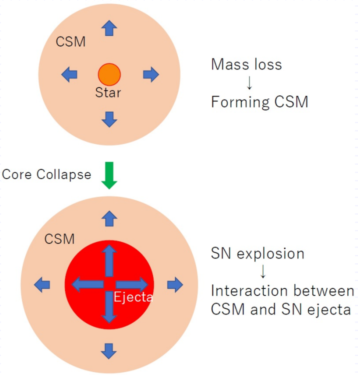
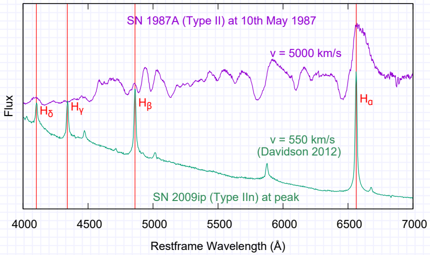
Supernova powered by circumstellar matter interaction

- SN explosion in a dense circumstellar matter (CSM) → interaction between SN ejecta and CSM
- $v_{\mathrm{CSM}} \ll v_{\mathrm{ejecta}} \rightarrow$ narrower emission line



Mass loss
↓
Forming CSM

SN explosion
↓
Interaction between CSM and SN ejecta

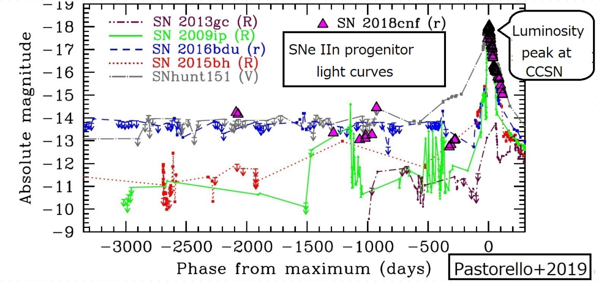


- H rich CSM → SNe IIn
- He rich CSM → SNe Ibn

- Mechanism of intense mass loss has not been completely clarified

Intense mass loss prior to SNe IIn

- For progenitors of SNe IIn, $\dot{M} \sim 10^{-4}$-$10^{-2} M_{\odot}/\mathrm{yr}$ (Taddia+2013)
  → Can not be explained by continuous mass loss model like Vink+2001
- Indicate episodic dynamical mass loss events



SNe IIn progenitor light curves

Luminosity peak at CCSN

Pastorello+2019

- Some progenitors exhibit significant fluctuation in the luminosity
  (e.g. SN 2018cnf Pastorello+2019; SN 2013gc Reguitti+2019; PTF12cjx Ofek+2014; SN 2009ip Pastorello+2013)
  → Related to intense mass loss?
- Mechanism and energy source of these mass loss have not been clarified

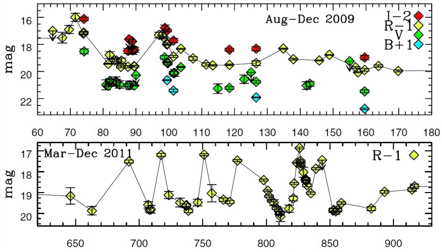
Mechanism and energy source of eruptive mass loss

- Candidate for the energy source
  - Pulsational pair instability (Woosley+ 2007, 2017)
  - Flash in a degenerate core (Woosley & Heger 2015)
  - Core neutrino emission weakens gravity (Moriya 2014)
  - Wave-driven mass loss (Shiode & Quataert 2014)
  - Burning instability (Smith & Arnett 2014)
  - Magnetic activity (Soker & Gilkis 2017)
  - Binary interaction (Danieli & Soker 2019)

- Dynamical simulation of the envelope into which energy is deposited
  - Super-Eddington wind
    Quataert+ (2016), Fuller (2017), Fuller & Ro (2018), Ouchi & Maeda (2019)
  - dynamical eruption
    Dessart+(2010), Owocki+ (2019), Kuriyama & Shigeyama (2020)

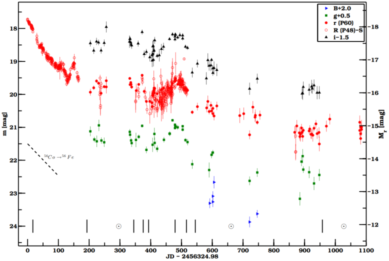
→ These papers study a "single dynamical eruption"

Eruptive mass ejection often repeats



SN 2009ip during mass loss phase

Pastorello+2013



Light curve of iPTF13z (Nyholm+2017)

- Light-curves of progenitors show repeated fluctuation (e.g. SN 2009ip, 2011ht, 2013gc, 2016bdu, PTF12cjx)

- Bumps in SN light-curves also indicate multiple mass loss phases (e.g. iPTF13z, SN 2010mc, 2006jd)

- A mass ejection can alter the density structure of the envelope and affect the subsequent mass ejection
- We investigate the dynamical evolution of the envelope into which energy is deposited twice by radiation hydrodynamical simulations

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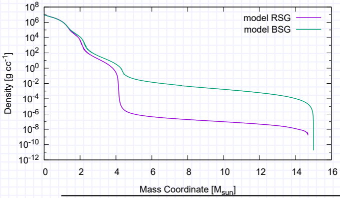
Initial models and energy injections

We make two progenitor models using MESA(Paxton+2011,2013,2015,2018,2019)

Name	$M_{\rm ZAMS}$	Z	R	$T_{\rm eff}$	$M_{\rm He\ core}$	$M_{\rm H\ env}$	$E_{\rm envelope}$	Time to CCSN
RSG	$15M_\odot$	0.02	$696R_\odot$	3500K	$4.1M_\odot$	$10.6M_\odot$	-5.6×10^{47} erg	11.2 yr
BSG	$15M_\odot$	0.0002	$76R_\odot$	10200K	$4.2M_\odot$	$10.8M_\odot$	-1.7×10^{49} erg	7.9 yr



- We deposit energy into the envelope of these models twice ($E_{\rm inj2}$ and $E_{\rm inj2}$) with a time separation $\Delta t_{\rm inj}$ and calculate dynamical evolution

Calculation model	Progenitor	$E_{\rm inj1}$ [erg]	$E_{\rm inj2}$ [erg]	$\Delta t_{\rm inj}$
RSG1-f (fiducial)	RSG	1.5×10^{47}	1.5×10^{47}	$1.0t_{\rm dyn}$ (98 day)
RSG1-s (short)		1.5×10^{47}	1.5×10^{47}	$0.5t_{\rm dyn}$ (49 day)
RSG1-m (medium)		1.5×10^{47}	1.5×10^{47}	$2.0t_{\rm dyn}$ (196 day)
RSG1-l (long)		1.5×10^{47}	1.5×10^{47}	$4.0t_{\rm dyn}$ (392 day)
RSG2-f (fiducial)		1.5×10^{47}	3.0×10^{47}	$1.0t_{\rm dyn}$ (98 day)
BSG1-f (fiducial)	BSG	6.0×10^{48}	6.0×10^{48}	$1.0t_{\rm dyn}$ (3.1×10^{5} s)
BSG1-s (short)		6.0×10^{48}	6.0×10^{48}	$0.5t_{\rm dyn}$ (1.5×10^{5} s)
BSG1-m (medium)		6.0×10^{48}	6.0×10^{48}	$2.0t_{\rm dyn}$ (6.1×10^{5} s)
BSG1-l (long)		6.0×10^{48}	6.0×10^{48}	$4.0t_{\rm dyn}$ (1.2×10^{6} s)
BSG2-f (fiducial)		6.0×10^{48}	9.0×10^{48}	$1.0t_{\rm dyn}$ (3.1×10^{5} s)

Radiation hydrodynamical simulation

- Equation system in Lagrangian coordinates

$$\begin{aligned} \frac{\partial(1/\rho)}{\partial t} - \frac{\partial(4\pi r^2 v)}{\partial m} &= 0 \\ \frac{\partial v}{\partial t} + 4\pi r^2 \frac{\partial p}{\partial m} &= g \\ \frac{\partial E}{\partial t} + \frac{\partial(4\pi r^2 v p)}{\partial m} &= vg - \frac{\partial L}{\partial m} \end{aligned}$$

$$v_{\mathrm{inner}} = 0, \quad r_{\mathrm{inner}} = \mathrm{Const.}, \quad P_{\mathrm{outer}} = 0$$

$$g = \frac{-Gm}{r^2}$$

- Solved by Godunov type scheme + PPM (Collela & Woodward 1984)
- HELMHOLTZ equation of state (Timmes & Swesty 2000)
- Radiative transfer is solved by flux-limited diffusion method (Levermore & Pomraning 1981, Shigeyama & Nomoto 1989)

$$L = -\frac{16\pi^2 a c r^4}{3\kappa}\frac{\partial T^4}{\partial m}\lambda$$

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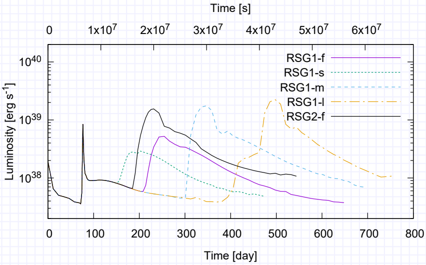
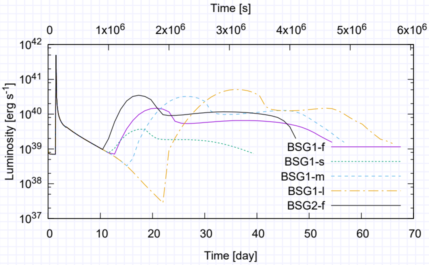
Light-curves



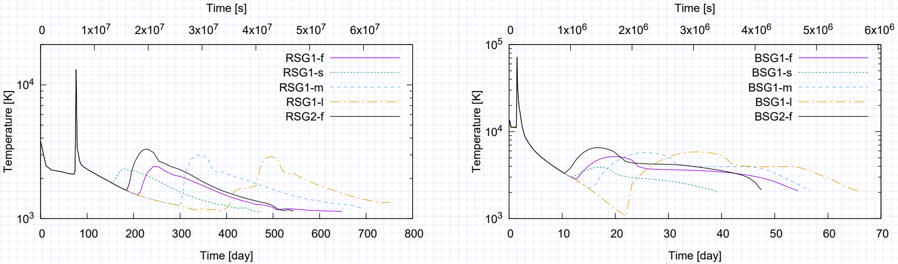


In the second eruption,

- luminosity rises and declines more slowly
  - → Because of longer dynamical time and photon diffusion from a shock in the more extended envelope
  - → Peak luminosity and brightening timescale seem to be determined by shock velocity $v_{\mathrm{explosion}}$
- the deposited energy is more effectively converted into radiation

Color evolution

- Second outburst is significantly redder compared with the first one



Amount of ejected mass

Amount of ejected mass for each eruption and model

model		First eruption (ΔM_1)	Second eruption (ΔM_2)
RSG1-f	($E_{\mathrm{inj2}} = E_{\mathrm{inj2}}$)	$0.013M_\odot$	$0.0015M_\odot$
RSG1-s			$0.0011M_\odot$
RSG1-m			$0.0013M_\odot$
RSG1-l			$0.0007M_\odot$
RSG2-f	($E_{\mathrm{inj2}} = 2E_{\mathrm{inj1}}$)		$0.73M_\odot$
BSG1-f	($E_{\mathrm{inj2}} = E_{\mathrm{inj1}}$)	$0.19M_\odot$	$0.51M_\odot$
BSG1-s			$0.59M_\odot$
BSG1-m			$0.55M_\odot$
BSG1-l			$0.56M_\odot$
BSG2-f	($E_{\mathrm{inj2}} = 1.5E_{\mathrm{inj1}}$)		$2.02M_\odot$

RSG1 ($E_{\mathrm{inj1}} = E_{\mathrm{inj2}}$) $\rightarrow$ $\Delta M_1 > \Delta M_2$

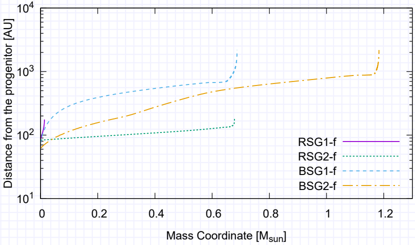
because of shock wave attenuation due to diffusion of photons in the second ejection

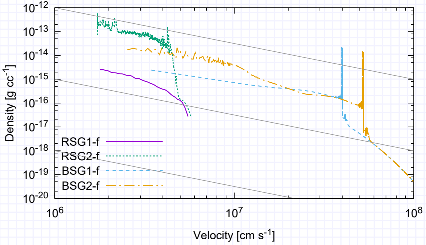
BSG1 ($E_{\mathrm{inj1}} = E_{\mathrm{inj2}}$) $\rightarrow$ $\Delta M_1 < \Delta M_2$

because of smaller binding energy of the envelope in the second ejection

- A factor of few difference in deposited energy make larger (by a few magnitude of) difference in the amount of ejected mass
- Model BSG requires ∼ten times larger amount of energy than model RSG to eject the same mass

Resultant CSM distribution at the time of core-collapse





- CSM lies at a few 100 AU (RSG) or several 100 AU (BSG)
- Velocity of CSM is almost decided by the escape velocity of the progenitor at the time of eruption

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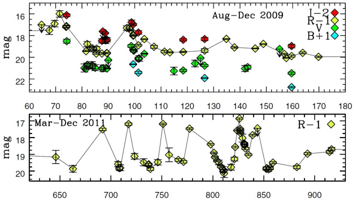
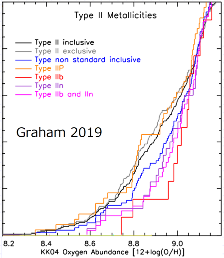
Discussion

- Unambiguous difference between the first and second mass ejection in terms of light-curves, colors, and the amounts of ejected mass even in the case of $E_{\mathrm{dep1}} = E_{\mathrm{dep2}}$
- Small difference in the deposited energy E_{dep} is amplified to a large difference in the amount of ejected mass ΔM
  → Related to wide variety of CSM mass in each SN IIn?
- The envelope of model RSG can be easily expelled compared with BSG
  → SNe IIn often occur in metal rich, high mass galaxy?



SN 2009ip during mass loss phase

Pastorello+2013



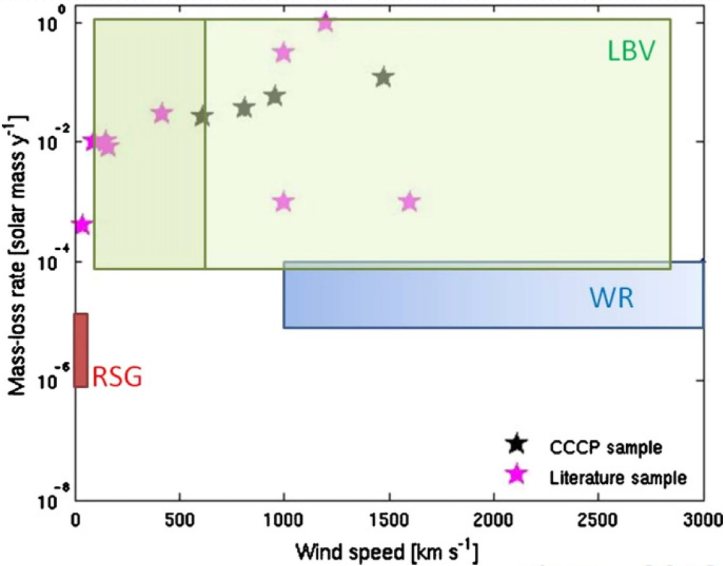
Graham 2019

Summary

- Progenitors of CSM interacting SNe (SNe IIn/Ibn) often experience intense mass loss associated with significant fluctuation of the luminosity.
- Mass loss rate is so high that it can not be explained by continuous wind mass loss model and should be treated dynamically.
- Mechanism and energy source of such events have not been clarified.
- Dynamical mass ejection may often occur repeatedly.
- A mass ejection alters the density structure of the progenitor and affects the properties of subsequent ejection.

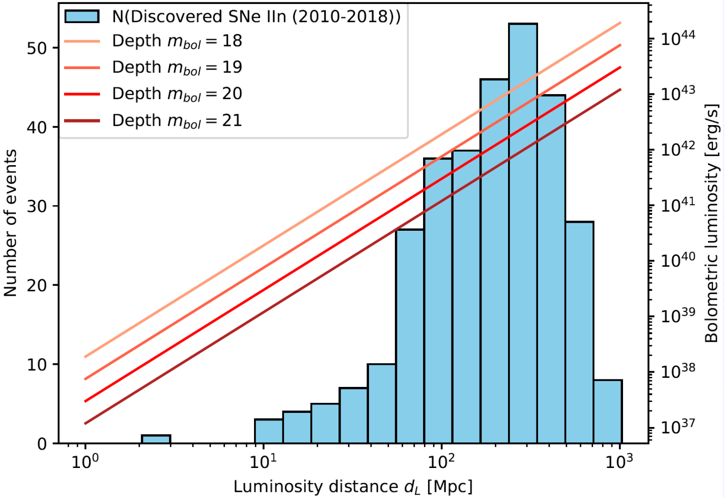
- We carried out radiation hydrodynamical simulations of the envelope into which energy is deposited twice.
- Our results show unambiguous difference between the first and second mass ejection in terms of light curves, colors, and the amounts of ejected unbounded mass even in the case of $E_{\rm dep1} = E_{\rm dep2}$.
- We did not deal with the origin of extra energy which has not been clarified so far, and it should be studied in our future work.

Appendix A



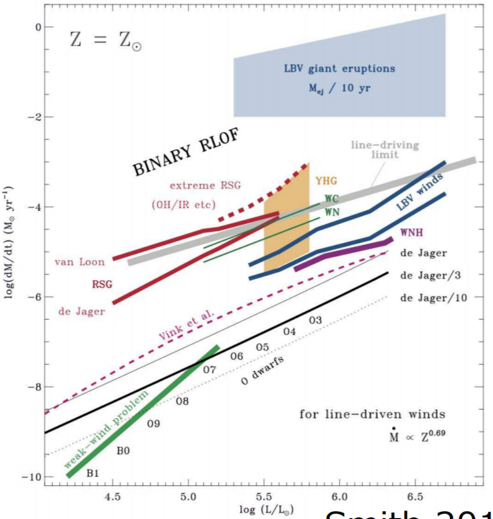
Kiewe+2012

Appendix B



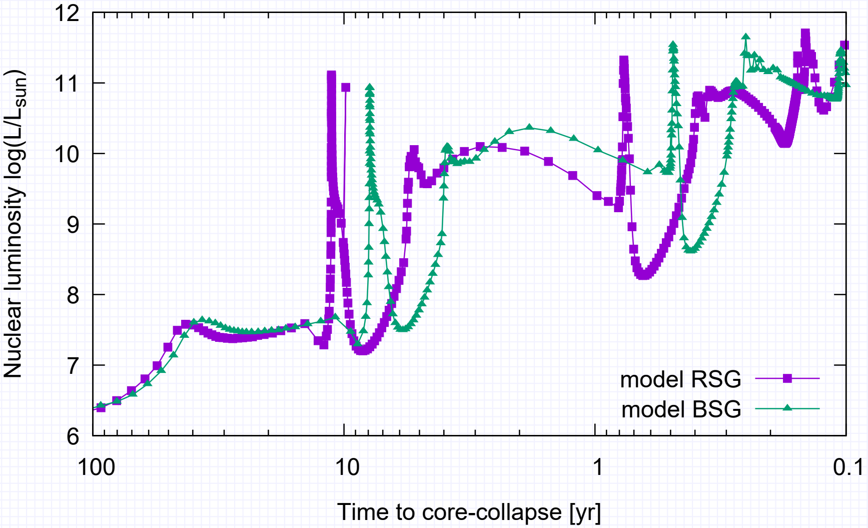
Kuriyama & Shigeyama (2020)

Appendix C



Smith 2014

Appendix D


12
11
10
9
8
7
6
Nuclear luminosity log(L/L_sun)
100
10
1
0.1
Time to core-collapse [yr]
model RSG
model BSG