Interacting supernovae

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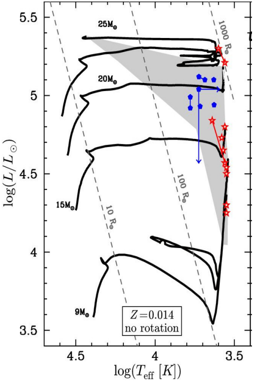
Talk outline

- What are supernovae and why are they important?
- Supernovae that interact with pre-existing circumstellar material
- Hydrodynamics of interactions
- Implications for observations
    - Light curves and spectral line profiles
    - Polarization signatures
- Comparison with observed supernovae
- Conclusions

What are supernovae and why are they important?

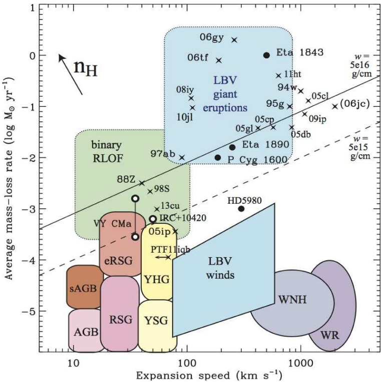
- Basic classification
  - Supernovae of type II
    Gravitationally collapsing very massive stars, mostly red supergiants (also yellow, blue, and LBVs)
  - Supernovae of type Ia
    Thermonuclear explosion of C-O white dwarf in a binary system
- Supernovae (SNe) chemically enrich their host galaxies and drive future generations of star formation
- The shock produced by a supernova probes the mass loss history of the progenitor system back to ages of $\sim$ 10 000 years before the explosion



Meynet+ 2015

SNe interacting with circumstellar material

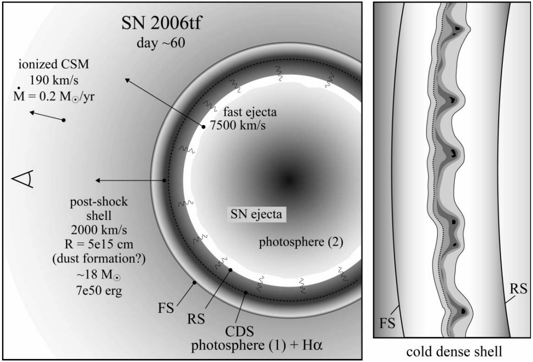
- The chief reason that they are extremely interesting is because they their progenitor may be wildly unstable long before explosion
- This has not been included in standard stellar evolution models
- Another reason they are interesting is because CSM interaction is a very efficient engine for making extremely bright super-luminous transients
- The CSM interaction may also be highly non-spherical, perhaps linked to binarity o the progenitor system



Plot of mass-loss rate as a function of wind velocity, comparing values for interacting SNe to those of known types of stars (Smith 2014)

SNe interacting with circumstellar material - basic physical picture

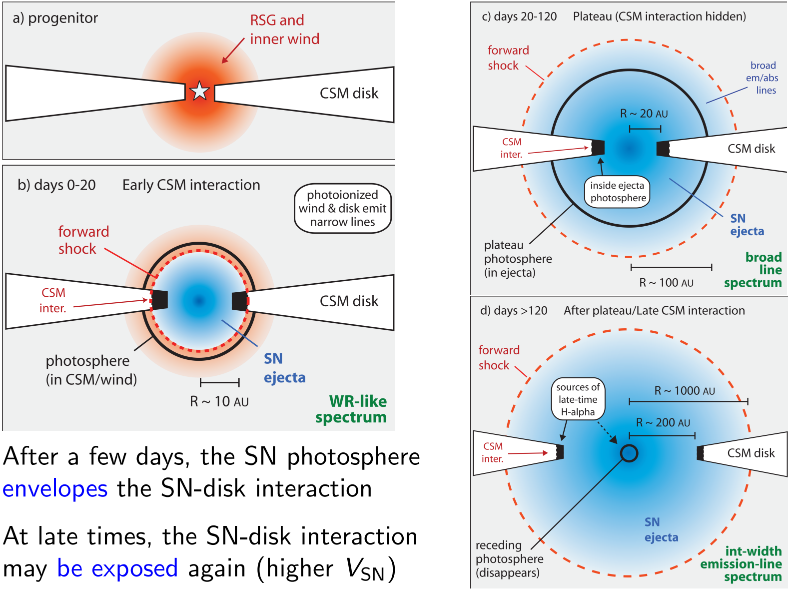
- When a SN explodes inside a dense CSM, four zones are delineated in the simplest picture (Smith+ 2008):



- The unshocked CSM outside the forward shock (FS) (photoionized)
- The swept-up CSM between FS and “cold dense shell” (CDS)
- The decelerated SN ejecta encountering the reverse shock (RS)
- The freely expanding SN ejecta inside RS

Basic physical picture

Sketch of the asymmetric SN-CSM interaction (Smith+ 2015)

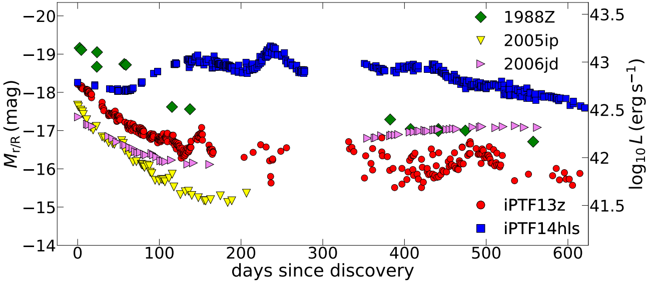


- After a few days, the SN photosphere envelopes the SN-disk interaction
- At late times, the SN-disk interaction may be exposed again (higher $V_{\rm SN}$)

Type IIn supernovae

Comparison of light curves of five prominent long-lasting type II SNe

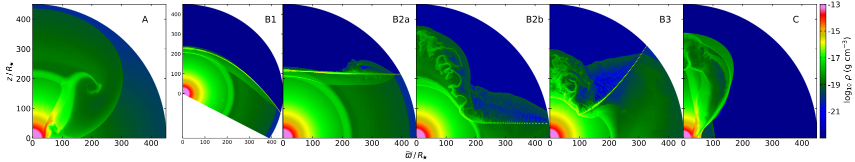
(Aretxaga+ 1999, Stritzinger+ 2012, Smith+ 2009, Nyholm+ 2017, Guillochon+ 2017)



- Most of the SNe (except iPTF14hls) are of type IIn, they showed a steep initial decline followed by a long slower decline
- Undulations and bumps in SN IIn light curves are rare but have been observed in a few cases (Nyholm+ 2017)
- Interaction of SN ejecta with clumpy CSM (cf. Calderón+ 2016, 2020) is also expected to produce bumps in the light curves

Hydrodynamics of interaction

- We performed high-resolution hydrodynamic simulations of a SN interacting with six types of aspherical CSM geometries (Kurfürst, Pejcha, & Krtička, accepted, in press; cf. also Kurfürst & Krtička 2019)



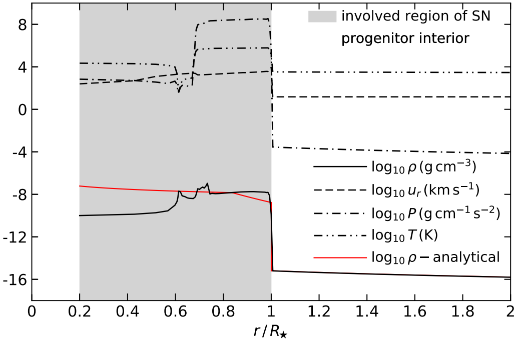
- Numerical setup:

- We use the own Eulerian hydrodynami code with radial grid composed of 60 zones for $0.2 \lesssim r/R_\star \lesssim 1$ and 6000 zones between $1 \lesssim r/R_\star \lesssim 450$ (outer boundary) (Kurfürst+ 2014, 2018, Kurfürst & Krtička 2017, 2019)

- The uniform polar grid with 480 grid cells covers $0 \lesssim \theta \lesssim \pi/2$ and 640 cells for $0 \lesssim \theta \lesssim 2\pi/3$

Hydrodynamics of interaction

Numerical setup - initial state of simulations



We calculate shock propagation through a realistic progenitor (nonrotating RSG of $15\,M_\odot$) using 1D RHD code SNEC (Morozova+ 2015)

Three CSM components: spherically symmetric SN ejecta, spherically symmetric stellar wind, and aspherical CSM

- Density ρ_{wind} of stellar wind is set to

$$\rho_{\mathrm{wind}} \propto r^{-2}$$

- Density profile of ρ_{disk} of equatorial disk is set to

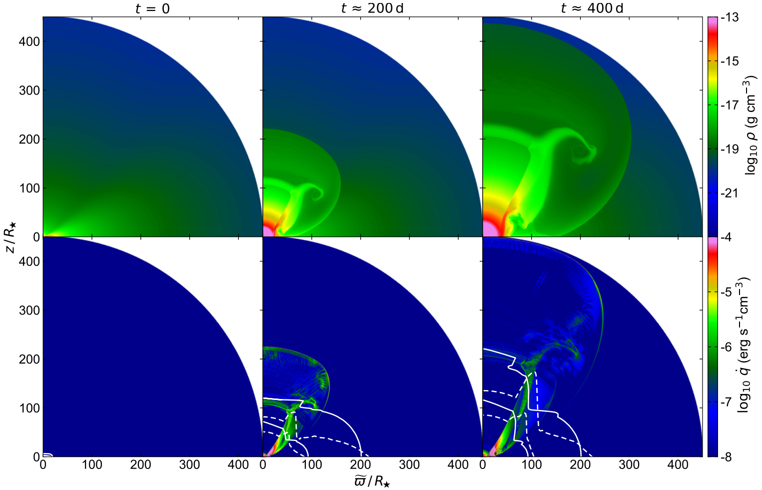
$$\rho_{\mathrm{disk}} \propto r^{-2}\exp\left[-\frac{z^2}{2H^2}\right], \text{ where } H \text{ is the disk scaleheight}$$

- Density profiles of other types of aspherical CSM are set numerically

Hydrodynamics of interaction

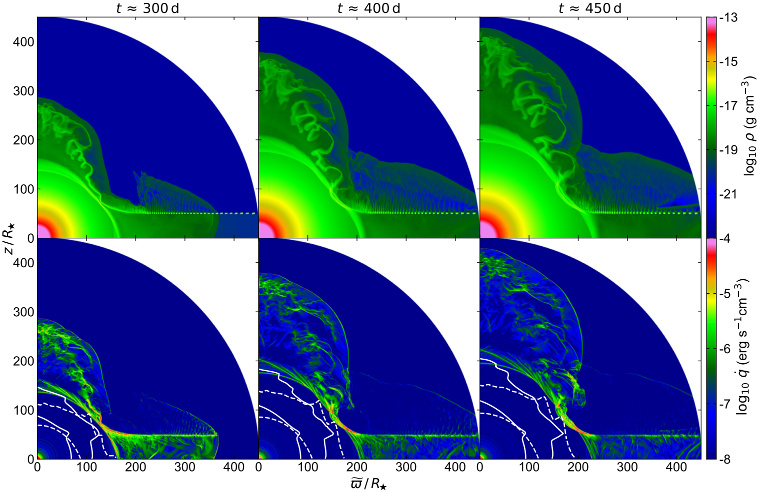
(Kurfürst, Pejcha, & Krtička, in press)

Stages in the evolution of the density ρ and shock heating rate $\dot{q}$ within SN ejecta interacting with circumstellar disk (model A).



Hydrodynamics of interaction

Stages in the evolution of ρ and $\dot{q}$ within SN ejecta interacting with a planar shell located closer to the progenitor (model B2b)



Hydrodynamics of interaction

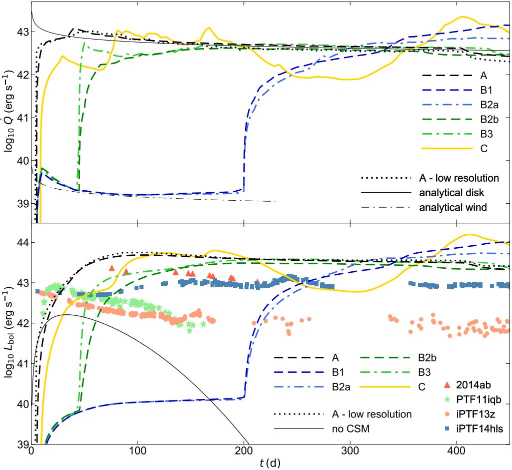
Animations of various models of SN interactions with asphercal CSM

(the previous quantities with r and θ velocity components):

- SN - circumstellar disk: model_A.mp4
- SN - colliding wind shell oriented to SN: model_B1.mp4
- SN - distant planar colliding wind shell: model_B2a.mp4
- SN - closer planar colliding wind shell: model_B2b.mp4
- SN - colliding wind shell oriented away from SN: model_B3.mp4
- SN interacting with bipolar lobes: model_C.mp4

Shock power as an internal power source

Estimates of shock heating rates and light curves from our simulations:



Comparison with observed LCs (Bilinski+ 2020, Smith+ 2015, Nyholm+ 2017, Arcavi+ 2017)

Models:

A - SN-disk

B1 - SN-colliding wind shell oriented to SN

B2a - SN-distant planar colliding wind shell

B2b - SN-closer planar colliding wind shell

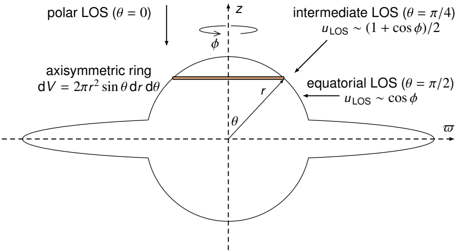
B3 - SN-colliding wind shell oriented away from SN

C - SN-bipolar lobes

Spectral line profiles

- Spectral line profiles can provide more insight into the ejecta geometry than the integrated light curves
- How can the observed spectral line profiles relate to different CSM geometries?
- Estimates of line profiles at late times, when the SN ejecta should be nearly transparent for radiation

Schema of the calculation of the line-of-sight velocity distributions

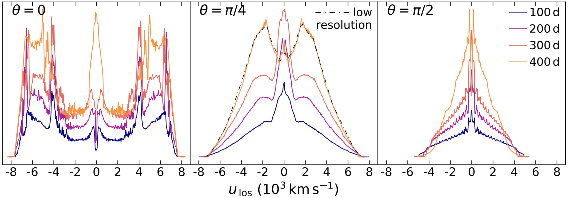


- Volume-weighted histograms of LOS velocities for $\theta = 0, \pi/4,$ and $\pi/2$ (cf. Jerkstrand 2017)
- We excise dense inner parts of the SN envelope, which correspond to the helium core

Spectral line profiles

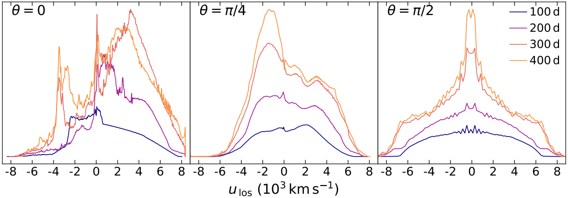
- Line-of-sight velocity distributions for our models:

A



SN - disk

B2b



SN - colliding winds planar shell

- Linearly scaled normalized distributions on the vertical axes
- Each column represents different viewing polar angle θ

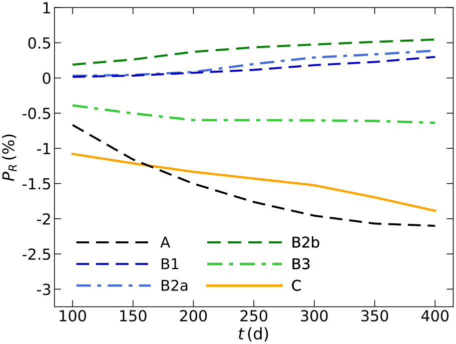
Polarization signatures

- The polarization degree is given by (Brown & McLean 1977, 1978)

$$P_R \simeq \bar{\tau}(1-3\gamma)\sin^2\theta$$

where $\bar{\tau}$ is the averaged Thomson scattering optical depth of the envelope and the shape factor γ is

$$\gamma = \frac{1}{<\rho>}\int_{R_{\mathrm{He}}}^{\infty}\int_{\mu=-1}^{1} n\mu^2\,\mathrm{d}r\,\mathrm{d}\mu$$

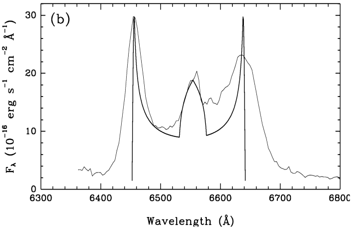


Evolution of relative polarization degree for our models. Values at selected times are given in Table 1 (in the following slide).

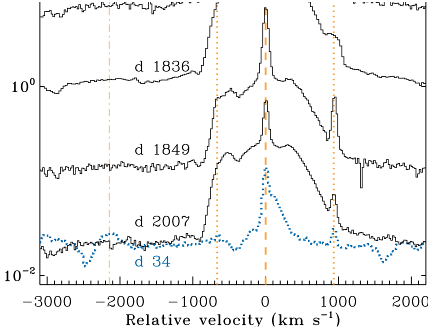
Comparison with observed supernovae

SN impostor UGC2773-OT

(Gerardy+ 2000)

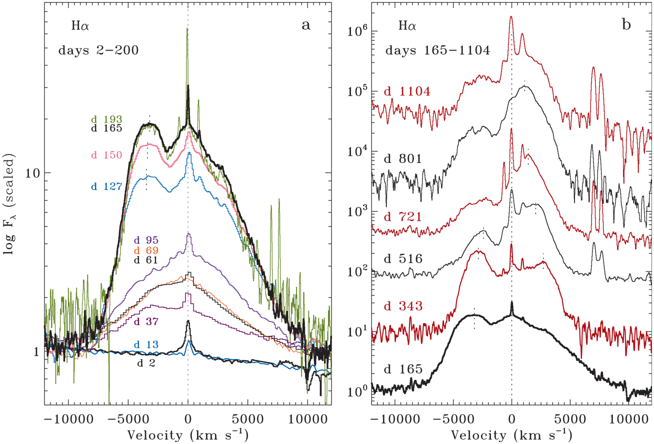


(Smith+ 2016, fragment of figure)



- *Left panel*: Observed Hα profile at day 22 and a line profile from a "toy model" for this emission (compare to our model A)
- Flat-topped profile with a possibility of double-peaked horns was argued to arise from bipolar lobes similar to what is seen in η Car → attributed to disk- or torus-like geometry (Jerkstrand+ 2017)

Comparison with observed supernovae



PTF11iqb

(Smith+ 2015)

- Initially a blueshifted peak of Hα emission, after $\sim$ 500 days a redshifted peak appeared and eventually dominated the emission
- Interaction with a colliding wind shell could consistently explain PTF11iqb (compare our models B2b and B3)

Conclusions

- In particular, we studied for the first time shock interaction with a colliding wind shell **within a binary systems**, we also compared the results to SN interactions with circumstellar disk and bipolar lobes

- Although the pre-explosion stellar $\dot{M}$ are typical for red supergiants ($\sim 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$) and parameters of colliding wind shells are consistent (cf. Wilkin+ 1996), the resulting $L_\mathrm{bol} \sim 10^{42}$ - $10^{43}\,\mathrm{erg\,s}^{-1}$ → this corresponds to what is observed in Type IIn SNe

- The time dependence of shock power shows short-term fluctuations or peaks with amplitudes $\lesssim 10\%$

- Colliding wind shells are positioned only on one side of the SN and could naturally explain the blue-red asymmetry of late-time line profiles (cf. Smith+ 2015)

Conclusions

- The distribution of line-of-sight velocities has the greatest discriminating power between different CSM geometries studied here
- Our models show the expected double-peaked profile for circumstellar disk and symmetric multipeaked flat-top profile for bipolar lobes
- Our estimates of relative polarization give values similar to what is observed (e.g., Dessart & Hillier 2011; Gal-Yam 2019), CSM in the form of disk and bipolar lobes leads to prolate shape of the ejecta and maximum P_R of 1–2%. Interaction with colliding wind shells leads to smaller P_R of $\lesssim 0.5\%$ and usually oblate shapes.