Radiative Transfer Modeling of Astrophysical Transients Powered by Circumstellar Interaction

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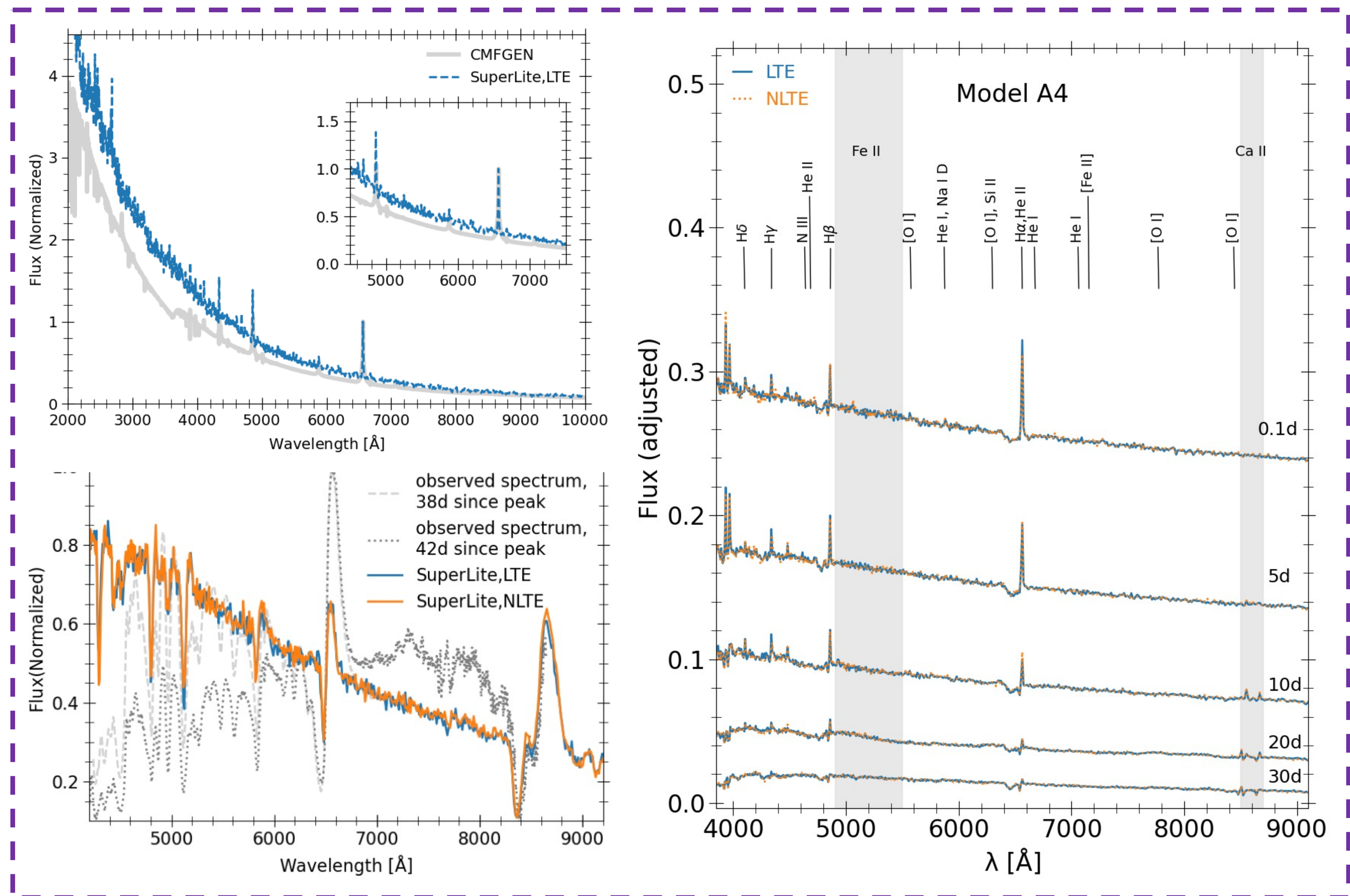
Abstract

Our work uses the new, open-source **SuperLite** code for detailed spectroscopic modeling of luminous transients, focusing on how variations in circumstellar material (CSM) mass, density profile and composition affect their spectral lines and light curves (LCs). Our state-of-the-art radiative transfer simulations show that spectral features, notably hydrogen and helium lines, vary markedly with CSM characteristics. In hydrogen-rich Type IIn SNe, dense CSM correlates with strong hydrogen emission, while hydrogen-poor interaction exhibits mostly featureless early spectra with transient helium emission lines, indicating rapid ionization. Our analysis highlights how distinct spectroscopic signatures can elucidate SN progenitor star mass-loss history and the physics of their CSM environments and provide crucial insights into the radiative properties of luminous and fast-evolving astrophysical transients.

SuperLite: A New, Open-Source MCRT Code

- Time-dependent Monte Carlo Radiation Transport (MCRT)
- MPI/OpenMP for enhanced parallel computing efficiency
- Open-source and initially 1-D, with plans for expansion to 2/3D
- Can process **non-homologous** input from radiation-hydrodynamics simulations of SN ejecta – CSM interaction.
- **Adjusted transport equations and opacity calculations for non-homologous ejecta** with corrected Doppler shift effects
- Implicit Monte Carlo (IMC) and Direct-Diffusion Monte Carlo (DDMC) for detailed particle tracking
- **Non-LTE physics for hydrogen**, covering emission, absorption, and ionization processes.



Top Left: Comparison between the SuperLite and the CMFGEN (Hiller & Dessart 2012) codes for an interacting Type IIn model that provides a good fit to SN2017hcc. **Bottom Left:** SuperLite model of a typical Type IIP SN spectrum computed in the LTE and the nLTE mode. Observed spectra of the Type IIP SN1999em at 38 and 42 days since peak luminosity are shown for comparison. **Right:** SuperLite synthetic spectra for a standard Type Iin SN model involving the interaction between 17.8 $M_\odot$ SN ejecta from an RSG progenitor star with 0.2 $M_\odot$ of H-rich CSM.

Simulation Pipeline (MESA→STELLA→SuperLite)

MESA
Single and binary massive star evolution in 1D.
Output: SN progenitor star structure

→

STELLA
2T Multi-Group Radiation Hydrodynamics of CSI in 1D spherical symmetry. Ability to attach CSM shells of different density profiles.
Output: 1D CSI profiles and lightcurves

→

SuperLite
1D MCRT in LTE or hydrogen NLTE in non-homologous velocity fields
Output: CSI spectra

The Models

Type II (H-rich) models (A & B Series)

Interactions between RSG/YSG progenitors and H-rich CSM

Type I (H-poor) models (C Series)

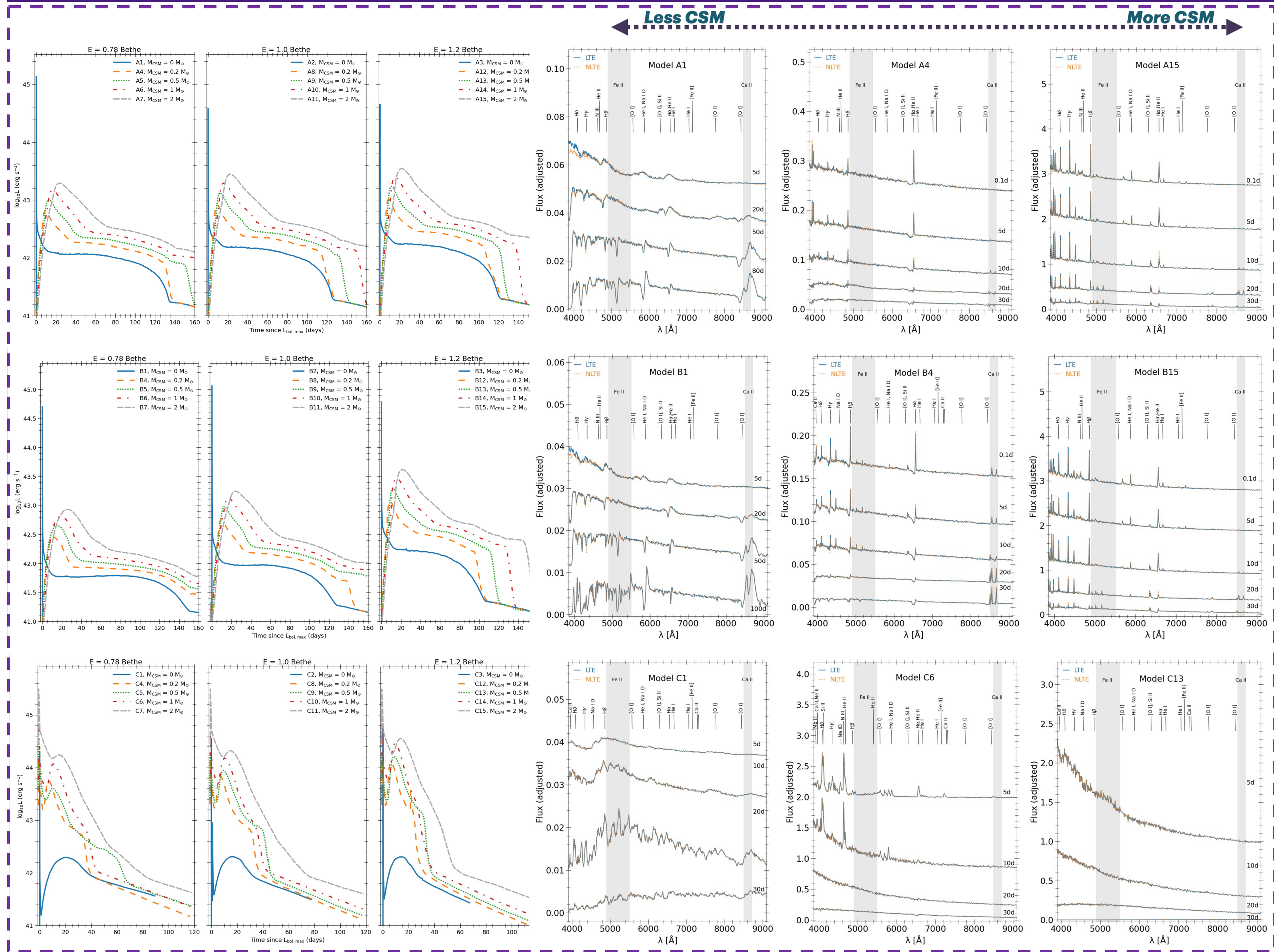
Interactions between BSG progenitor and H-poor or H/He-poor CSM

CSM properties

M = 0.2 – 2 $M_\odot$, Mdot = 0 – 0.25 $M_\odot$ / year, $\sim r^{-2}$, r^0 (constant), Gaussian density profiles, H-rich vs H-poor

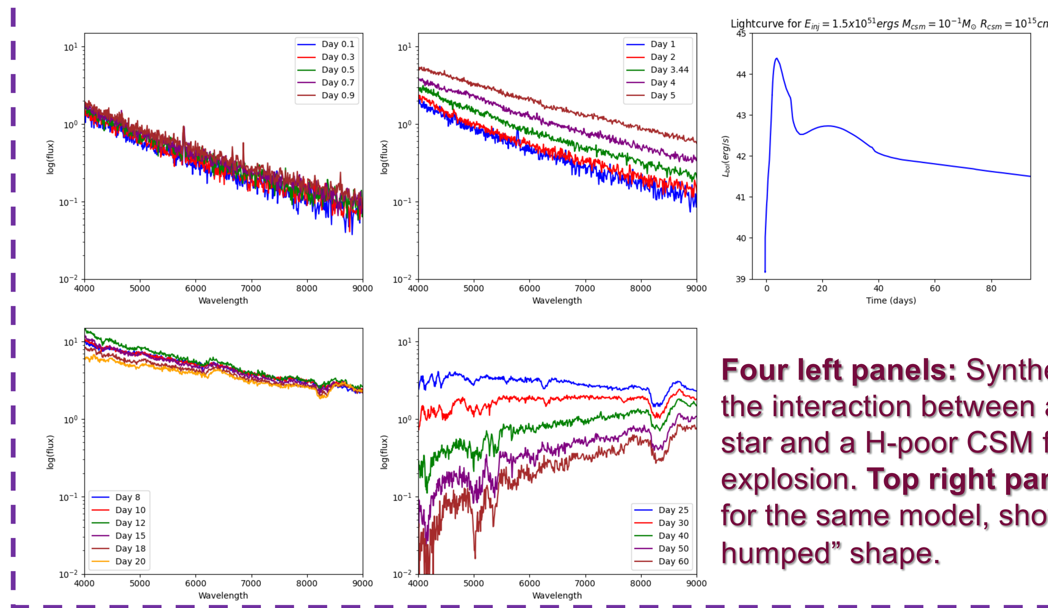
	A-Series	B-Series	C-Series
	RSG + CSM with r^{-2} density profile	YSG + CSM with r^{-2} density profile	BSG + CSM with r^{-2} density profile
Envelope:	64% H and 34% He	62% H and 36% He	0% H and 84% He
E_{SN}	0.8 - 1.2 x 10^{51} erg	0.3 - 1.0 x 10^{51} erg	0.8 - 1.5 x 10^{51} erg
M_{ej}	19 M_{sun}	12 M_{sun}	11 M_{sun}
M_{CSM}	0 - 2 M_{sun}	0 - 2 M_{sun}	0 - 2 M_{sun}
R_{CSM}	5 x 10^{15} cm	5 x 10^{15} cm	6 x 10^{15} cm
M_{dot}	0 - 0.25 M_{sun} / yr	0 - 0.25 M_{sun} / yr	0 - 2 M_{sun} / yr

Results I: Synthetic Spectra of Interacting SNe

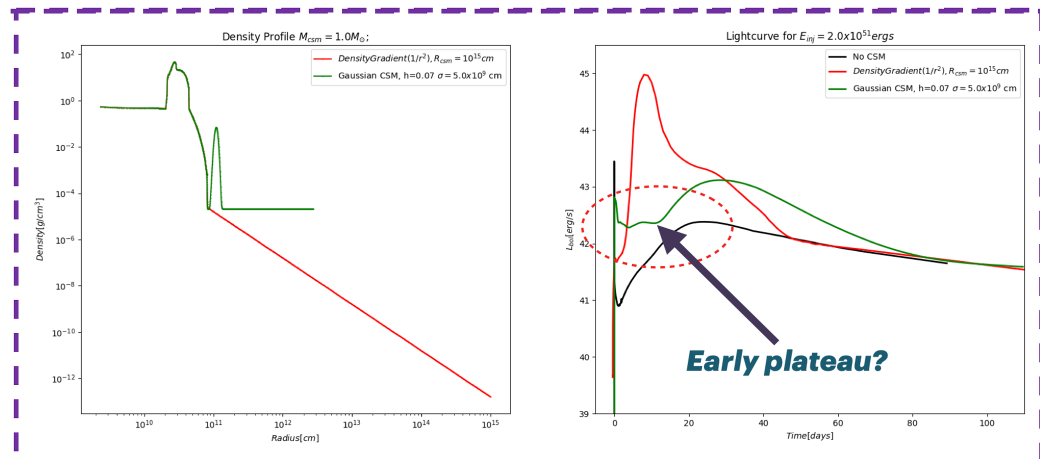


Synthetic STELLA LCs (left panels) and time-series of synthetic spectra (right panels) for the A, B and C-series models. Please note that most of these events incur CSM interaction with dense CSM shells of different properties. The results for our A series, the B series and the C series models are shown in the top, middle and bottom panels accordingly.

Results II: Interactions with H-poor CSM



Four left panels: Synthetic SuperLite spectra of the interaction between a stripped BSG progenitor star and a H-poor CSM for 0.1 - 60 days since explosion. **Top right panel:** Synthetic STELLA LC for the same model, showcasing a "double-humped" shape.



Left Panel: Density profile for BSG-type SN ejecta with a steady-state ($\sim r^{-2}$) wind (red curve) and a Gaussian-shaped CSM shell (green curve). **Right Panel:** STELLA LCs resulting from the interaction between the BSG-type progenitor and the two CSM density profiles.

Conclusions

- CSM with diverse properties result on variations in SN types, with more massive CSM leading to stronger Hα and Hβ emission lines.
- H-poor CSM typically results in bright, fast-evolving SLSN-I/Ibn events and early, weak helium lines transitioning to a featureless spectrum.
- Larger progenitor radii are associated with stronger Hα emission.
- SN ejecta – CSM interaction for stripped-envelope progenitors produces brighter light curves but weaker hydrogen lines.
- Gaussian CSM density profiles lead to an early plateau in light curves.
- Expanded analysis will include varied CSM geometries in 2D to refine understanding of spectroscopic signatures and their dependence on viewing angle.

References

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SuperLite!