Modeling the early peak of Type Ibc supernovae

Ryotaro Chiba, Takashi Moriya

National Astronomical Observatory of Japan

Abstract

Many supernovae (SNe) exhibit signatures of interaction between their ejecta and circumstellar matter (CSM), which is a potential source for cosmic high-energy neutrinos. Although the CSM around Type II SNe has been well-studied, less is known about that surrounding Type Ibc SNe. Using 1D radiation-hydrodynamics simulations, we investigate the properties of CSM around Type Ibc SNe by modelling the early peaks in their light curves (LCs) which are attributed ejecta-CSM interaction and are observed in ~5% of Type Ibc SNe. We derive CSM properties by fitting the multi-band LCs of a selected SN. Our findings suggest that a previous study relying on analytical model may have overestimated the CSM mass.

1. Introduction

SN (Supernovae)

- Type II SN: explosion of RSGs with extended H-rich envelope
- Type Ibc SN: explosion of stars whose envelope is stripped

CSM (Circumstellar material)

- Dense material expelled by SN progenitors before explosion
- Collision between SN ejecta and CSM powers EM radiation across multiple wavelengths (optical, radio, X-ray) and may also produce high-energy neutrino (e.g., Murase 2024)
- Observable signatures include narrow spectral features and diversity in LCs (enhanced luminosity, extended timecales)
- Early peaks in Type Ibc SNe are also usually attributed to CSM as their progenitors lack extended envelopes

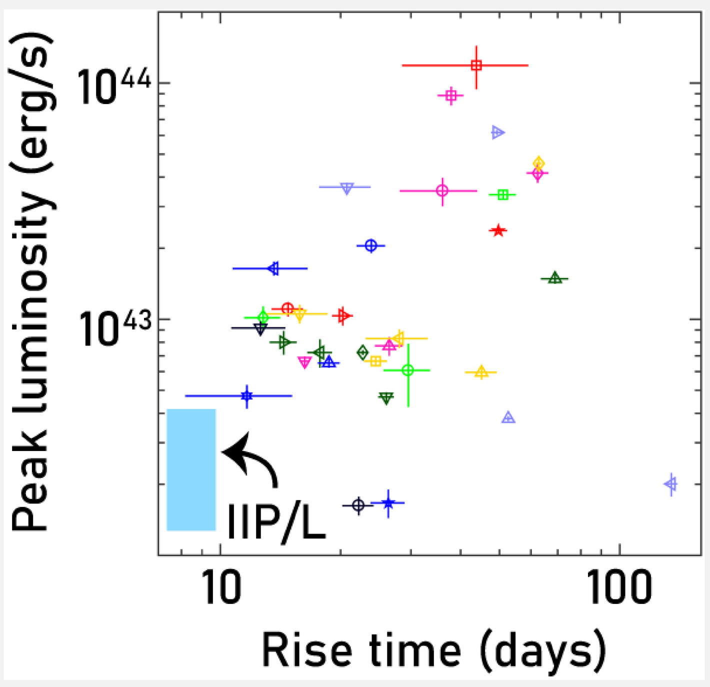

Fig 1: timescale & luminosity of interacting SNe (Nyholm+20)

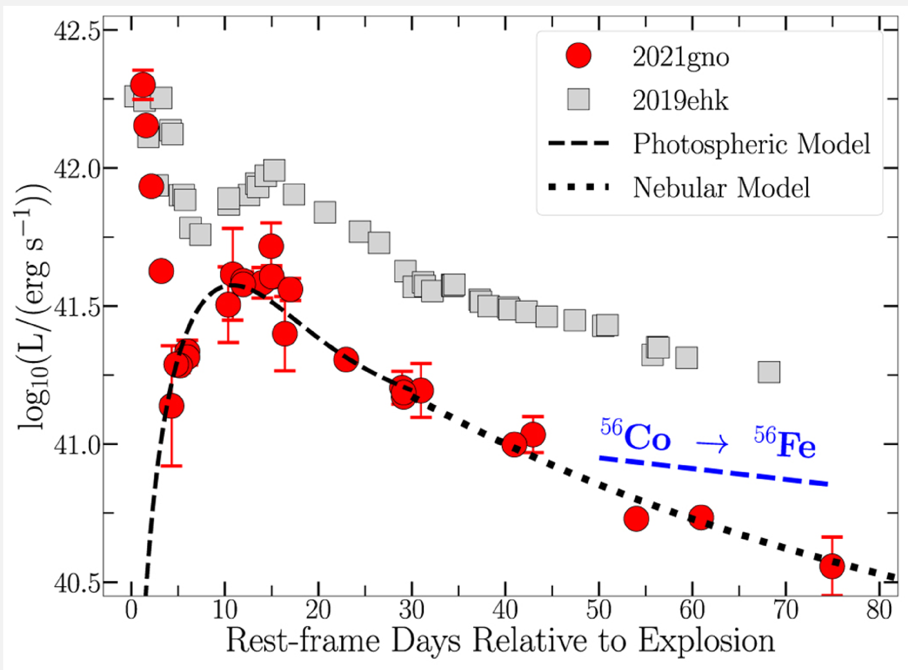

Fig 2: LCs of two Type Ic SNe with early peaks (Jacobson-Galán+23)

Previous studies:

- CSM around Type II SN: abundant observational data & analyses (e.g., Bruch+23)
- CSM around Type Ibc SN: not much is known!
- Recent study by Das+24
  - Identified early peaks in 19 Type Ibc Sne (rate: ~ 5%) in the ZTF sample
  - Estimated CSM parameters through analytical modelling of these early peaks

Systematic investigation of Type Ibc SNe using numerical simulation is lacking… Detailed modelling is warranted

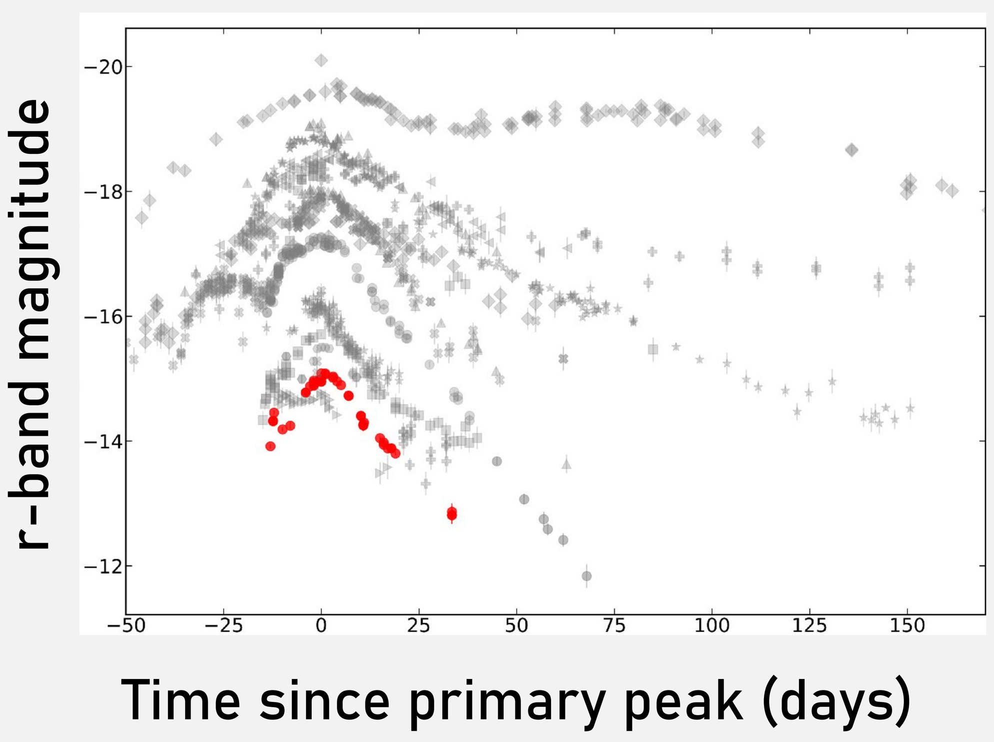

Fig 3: LC samples collected in Das+24

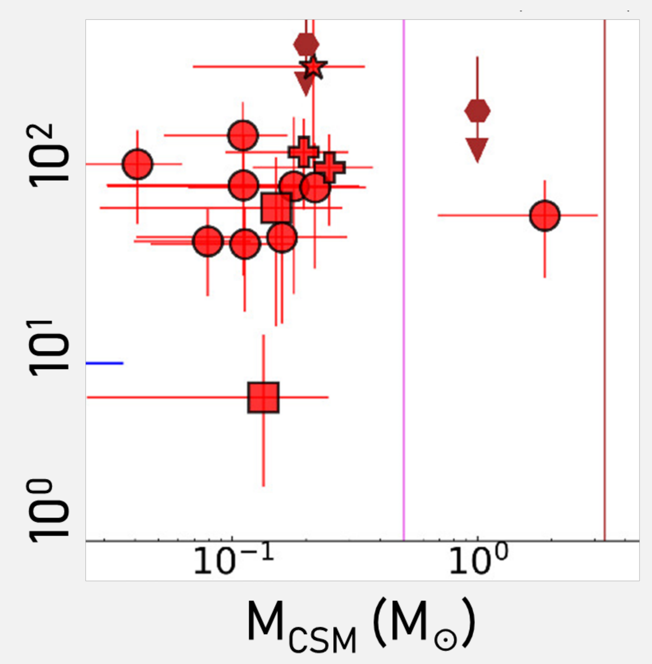

Fig 4: CSM properties inferred in Das+24

2. Construction of SN models

- We build upon the CO21 model (Iwamoto+94)
  - Model of a CO star 1 day after explosion
  - Shrink the system assuming homologous expansion
- Scale the parameters
  - Explosion energy E_{ej}, ejecta mass M_{ej}
  - ^{56}Ni mass M_{Ni}, extend of ^{56}Ni mixing
- Attach CSM with different parameters
  - CSM mass M_{CSM}, CSM radius R_{CSM}
- Solve the model using 1D radiation-hydrodynamics code STELLA

3. Results (preliminary)

Testing our theoretical LCs with SN 2022oqm (Irani+24)

- Type Ic SN with an early peak
- Three phases in its LC: early peak (~1 d), middle excess (2~10 d), main peak (10~ d)

Our model successfully reproduced the early peak with:

- R_{CSM} = 5 x 10^{14} cm
  M_{CSM} = 5 x 10^{-3} $M_\odot$
- Significantly different from values inferred in Das+24:
  (R_{CSM} = 2 x 10^{12} cm, M_{CSM} = 1 x 10^{-2} $M_\odot$)
- Extent of ^{56}Ni mixing may account for middle "excess"?

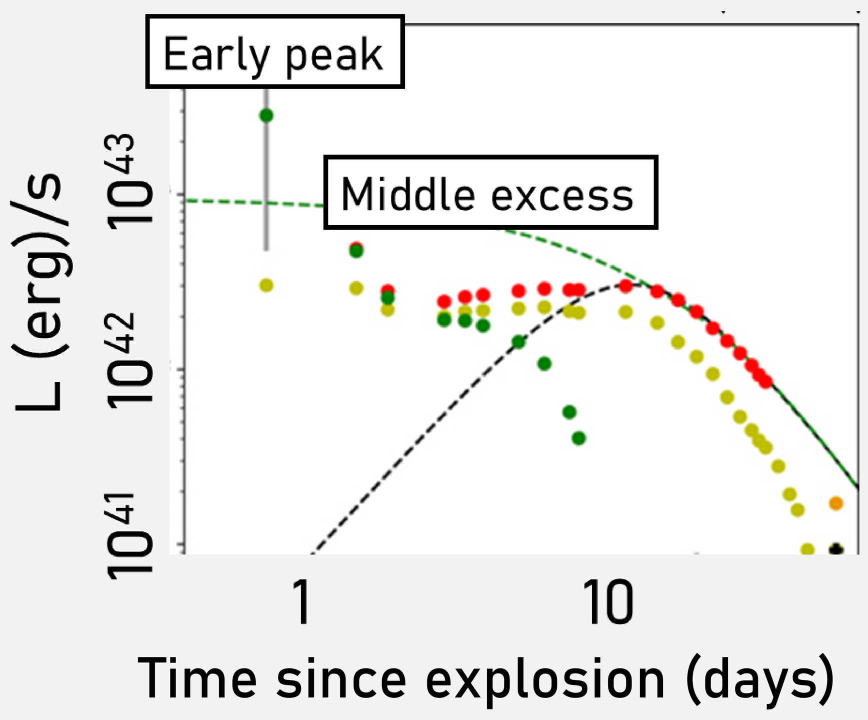

Fig 5: Bolometric LC of SN 2022oqm (Irani+24)

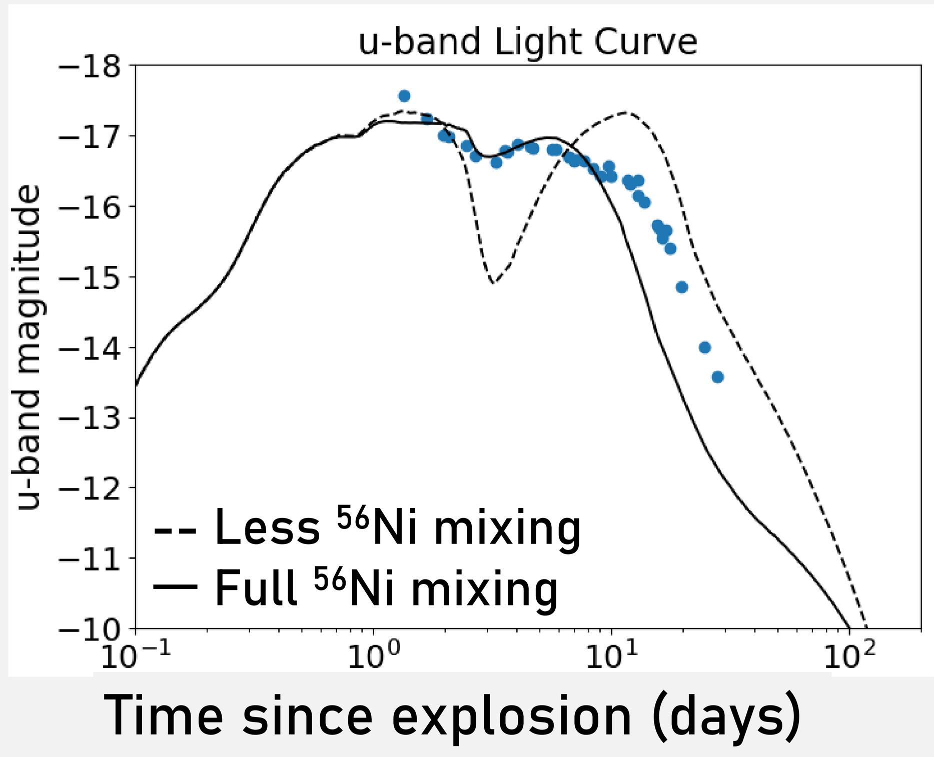

Fig 6: LC of SN 2022oqm compared to our synthetic LC

4. Discussion

- Analysis in Das+24 assumes that:
  - Energy imparted to CSM by the shock is a free parameter
  - Early peak is entirely powered by shock cooling emission
- Our model predicts smaller contribution from shock cooling

5. Summary

- Early peaks in Type Ibc SNe as a probe of CSM
- Previous study may have overestimated CSM masses
- Our model grid will be useful for analyzing the large volume of LC data expected from LSST
- Our results will provide constraints on the potential contribution of CSM around Type Ibc SNe to high-energy neutrino production

References

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