Exploring the Physics of Supernovae Shock Breakout

Shock breakout (SBO) marks the first release of photons during supernovae (SNe), providing a glimpse into the progenitor's outer layers and immediate surroundings. Recent UV and X-ray surveys uncover delayed and extended SBO signals in Type II SNe (Yaron et al., 2017), inconsistent with predictions from smooth wind models.

These anomalies suggest the presence of dense, confined-shell circumstellar material (CS-CSM) shaped by binary interaction or eruptive mass loss shortly before collapse. Such structures can significantly alter the breakout signature, yet their multidimensional impact on light curve and spectral evolution remains poorly understood.

This project will address that gap using `CASTRO`'s radiation-hydrodynamic (RHD) framework with multigroup flux-limited diffusion (MGFLD) to simulate SBO through complex CS-CSM. By integrating binary evolution models and resolving angular and spectral effects, we aim to quantify how CSM geometry affects breakout timing and observables. Additionally, machine learning will be used to emulate these effects across parameter space (Maltsev et al., 2024; Soultanis et al., 2025), enabling fast prediction and survey interpretation.

II. Proposed New Studies

The applicant, Wun-Yi Chen, is a Ph.D. candidate at National Taiwan University (NTU) and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). He has studied SBO in SN 1987A using the `CASTRO` radiation-hydrodynamic code (Chen et al., 2024), focusing on how radiation-driven instabilities and CSM structures influence mixing and emission from shock launch to breakout. His simulations demonstrated that mixing within optically thin ejecta layers alters both emission features and color evolution in ways not captured by 1D models, underscoring the importance of multidimensional effects in shaping early-time observables.

In more complex environments—where SN ejecta interacts with dense, asymmetric CSM formed via eruptive mass loss or common-envelope evolution (Yaron et al., 2017; Maltsev et al., 2024)—significant large-scale mixing and anisotropic emission are expected to impact early light curves and spectra. However, most existing models rely on 1D frameworks (Moriya et al., 2014; Lovegrove et al., 2017) or 3D simulations with gray radiative transfer (Goldberg et al., 2022), both of which lack the spectral resolution and angular sensitivity needed to fully capture SBO–CSM interactions.

To overcome these limitations, this project will conduct new multidimensional RHD simulations to examine the interplay among SBO radiation transport, CS-CSM morphology, and fluid mixing. By resolving these processes, we aim to produce realistic synthetic light curves and spectra that capture the full physical complexity of SBO in massive star explosions.

Design and Methodology

We use `CASTRO`'s adaptive mesh refinement (AMR) and GPU acceleration to simulate SBO dynamics with multigroup flux-limited diffusion (MGFLD) (Almgren et al., 2010; Almgren et al., 2020; Zhang et al., 2013), enabling frequency-dependent RHD

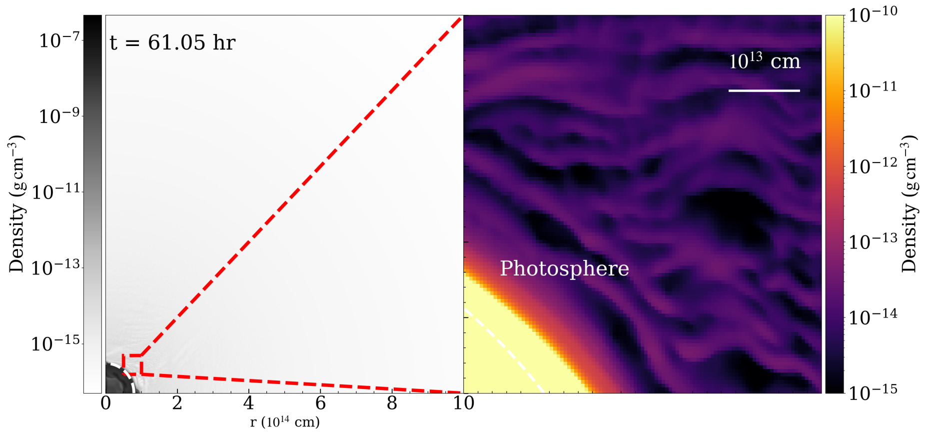

Figure 1 *The figure highlights early-time breakout structures and precursor signatures that precede shock emergence, unique to SBO-phase modeling.*

that captures SBO emission from infrared to soft X-rays. This is essential, as real SBO observations are dominated by short-wavelength components, and our previous studies show that neglecting spectral color evolution can lead to significant misinterpretation of the breakout timescale (Chen et al., 2024).

Figure 1 shows Rayleigh–Taylor instabilities and unshocked radiation precursors emerging in simulations of red supergiant (RSG) SBO. The expanding shock width enhances photon escape, shifting breakout durations from seconds to days. These non-linear structures significantly shape SBO emission and temporal profiles.

Initial conditions for the CS-CSM simulations will be derived from binary stellar evolution models developed by the Heidelberg Institute for Theoretical Studies (HITS) Physics of Stellar Objects (PSO) group (Vetter et al., 2024; Wei et al., 2024). These include both steady winds and confined-shell CSM formed through late-stage mass loss (Yaron et al., 2017; Tsai et al., 2023; Ou et al., 2023), and will be mapped onto a breakout framework tailored for BSG and RSG progenitors (Chen et al., 2024).

To efficiently explore parameter space, we will train neural networks to emulate SBO light curves across diverse CSM and progenitor's configurations.

Practical Implementation

Complex SBO requires advanced numerical techniques and substantial computational resources. Each phase will involve close collaboration between the applicant and the host group, including regular discussions to assess progress and adjust simulation strategies. Following the Sandwich Program, remote collaboration will continue through scheduled online meetings, with an emphasis on data analysis and manuscript preparation. This structured plan ensures coordinated efforts, efficient use of HPC resources, and timely scientific outcomes.

The planned timeline and milestones are as follows:

1. **Months 0–1**: Set up HPC environments (e.g., `KAWAS`, `NERSC`) and ensure stable network access and data pipelines. Generate initial 1D CSM profiles using `MESA` binary models and observational constraints.
2. **Months 2–5**: Conduct 2D `CASTRO` simulations of SBO through wind and confined-shell CSM profiles. Validate optical depth structure and breakout

timescales. Run corresponding 1D simulations for baseline comparison. Test morphological mapping consistency between PSO-generated CSM profiles and `CASTRO` inputs, including asymmetries and outflow velocities.

3. **Months 6–9**: Expand simulations to progenitors with varying masses, metallicities, and explosion energies. Analyze breakout diagnostics and apply machine learning to generalize trends across parameter space.
4. **Months 10–12**: Compare synthetic light curves and spectra with early-phase Type II SN observations. Finalize manuscript in collaboration with the PSO group and plan follow-up proposals.

Scientific Significance and Broad Impact

This project focuses on the final moments of massive star evolution, simulating CS-CSM SBO shaped by 3D common-envelope processes. Using multigroup radiative transfer in `CASTRO` and progenitor structures from `MESA`, we aim to establish physical links between late-stage mass loss and early-time SBO observables, including breakout duration and flash-ionized features in Type II SNe.

The simulations will yield spectra and angle-dependent light curves that characterize how CSM geometry alters early-time observables. To accelerate interpretation, we will build machine learning models that predict SBO signatures across diverse progenitor and CSM scenarios, enabling synergy with time-domain surveys.

In addition to its scientific outcomes, the project supports long-term collaboration between Taiwan and Germany through student exchange and joint modeling efforts. The applicant's current DAAD–NSTC placement at HITS builds on a broader institutional partnership, which includes ongoing collaboration between the host group and the applicant's supervisor, Dr. Ken Chen, who is currently a visiting scholar at HITS. This growing research network provides a strong foundation for sustained cooperation in stellar evolution studies.

VI. Supplemental information

Host institute – Heidelberg Institute for Theoretical Studies (HITS)

HITS stands as a leading center for theoretical studies in Germany, particularly in the field of astrophysical sciences. HITS encompasses several groups dedicated to astrophysical research, making substantial contributions to the advancement of the field. My host, Professor Friedrich Röpke, is a globally recognized expert in stellar evolution and explosions. His expertise will be instrumental in providing valuable insights into modeling the CSM of massive stars as part of our research program.

Additionally, we are fortunate to have access to computational resources in Germany, Taiwan, and USA, which will empower us to conduct sophisticated simulations and analyses crucial to our scientific inquiries and discoveries.

Qualifications

The applicant is a Ph.D. candidate at NTU and ASIAA, supervised by Dr. Ken Chen. His proposed thesis focuses on multidimensional RHD simulations of SBO using `CASTRO`. He is the lead author of the first published 2D MGFLD simulation of a SN 1987A breakout (Chen et al., 2024), which revealed the significant role of fluid instabilities with radiation precursors in shaping early X-ray and UV light curves.

A second study extending this approach to RSG progenitors with different steady mass-loss rates is currently in preparation. A third paper, based on confined-shell CSM shaped by binary evolution and eruptive events, is planned as part of this proposed project. These three papers focused on BSG, RSG, and confined-shell breakout environments will constitute essential chapters in the applicant's Ph.D. thesis and are necessary to complete its core scientific framework.

The applicant is currently hosted at HITS through the DAAD–NSTC Summer Program, collaborating with PSO group led by Prof. Friedrich Röpke. During the first phase of the program, he has developed a deeper understanding of shock breakout through extensive discussions with the group, laying the foundation for long-term collaboration. The group's internationally recognized expertise in common-envelope evolution, multidimensional explosion modeling, and machine-learning–based progenitor inference strongly complements the applicant's work. Their ongoing efforts in 3D binary simulations, data-driven stellar structure modeling, and synthetic light curve generation provide critical resources that directly strengthen both the modeling and observational aspects of the proposed research.

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