Supernovae Shock Breakout and CSM Interaction

The summer programme at the Heidelberg Institute of Theoretical Studies (HITS) has come to a fruitful end. This report is divided into three parts: first, an overall review of my stay, including discussions with scientists and contributed talks at different events; second, a revisit of the original project goals and preliminary results achieved through discussions and research synergies with experts in Germany; finally, reflections on how I maximized this opportunity during my stay and the outlook for future studies.

II. Project Overview and Acknowledgement

First of all, I sincerely thank the NSTC and DAAD for providing this opportunity, and my supervisor Ken for contacting Fritz to host me at HITS.

The origin of my study is closely tied to my multi-dimensional shock breakout models with radiation transport, combined with the expertise in multi-D interacting supernova simulations in Fritz's PSO group, which can provide new perspectives on the final fate of binaries.

After the DAAD introductory seminar in Bonn, Fritz and I discussed the possible schedule, and I contributed two short talks and several discussion within the group members. This helped me to better understand the research frontier of binary common envelopes and their potential improvements.

HITS offers a highly interactive atmosphere across different disciplines, all focused on modeling and solving complex problems using numerical and theoretical approaches. Despite its relatively small scale, the institute is renowned for having cultivated three MPI directors.

During my stay, I had many opportunities to discuss with researchers studying binary star mergers, common envelopes, massive stars, and machine learning. This happened through regular PSO group meetings as well as subgroup meetings on stellar physics and common envelopes. The low hierarchy between students and professors strongly encouraged the exchange of ideas. Even Kai, the HITS director, openly shared the challenges of securing cluster funding and how political and educational systems are reshaping the German academic environment. In general, German researchers are less in favor of the concept of "work–life balance," arguing instead that if research is one's passion, then working is living. This view, however, is supported by the relatively egalitarian social system in Germany, which contrasts with Taiwan's higher inequality (gini ratio).

Beyond HITS, I also had the chance to visit Bonn and MPA Munich, where I gave talks and pushed myself further beyond my comfort zone. In Bonn, Prof. Norbert provided excellent insights into shock breakout and CSM interaction. At MPA, Stephan, a member of the PSO subgroup on stellar physics, hosted us and invited me to give a talk. This led to stimulating discussions with developers of 3D progenitor models and observers of Pop III stars.

I made sure to acknowledge NSTC and DAAD in every talk and news contribution. Our related work of SN 1987a Shock Breakout also received the 2025 NCTS Student Outstanding Paper Award, which enhance the standing point of our deeper and broader investigation into shock breakout physics, and better understanding of

Figure 1 *The historic building of HITS. My office is on the second floor with a perfect terrace where people enjoy view and coffee. The design of the institute focus on cross discipline communication and numeric calculation.*

our universe through this hundreds time luminous event than normal SNe. Overall, this summer was a truly fruitful, yet happily exhausting, research journey.

III. Goal Review and Results

The main goal of this summer programme was to build a model that can describe realistic circumstellar medium (CSM) interactions during shock breakout (SBO), using multigroup flux-limited diffusion (MGFLD) transport in `CASTRO`. While the work is still in progress, three practical tools were developed during my stay:

1. observational fitting of density profiles,
2. 1D data read-in capability,
3. 2D hydrodynamical mass-loss history and CSM evolution.

Discussions at HITS and with visiting researchers also inspired new directions, leading to preliminary results:

1. 2D model remapping applied to red supergiant (RSG) and 3D progenitor models,
2. `SEDONA` calculations to connect SBO simulations with observational calibration,
3. exploration of binary interaction imprints on stellar atmospheres, including the

Figure 2 *The commute trail from the Nekar river to HITS, although beautiful but should the flood come with heavy rain the only transportation will be a limited shuttle bus.*

Figure 3 *The coffee break corner at HITS is everyday 9:00, 13:00, and 16:00, a perfect spacetime for brainstorming scientific ideas and sharing life experiences.*

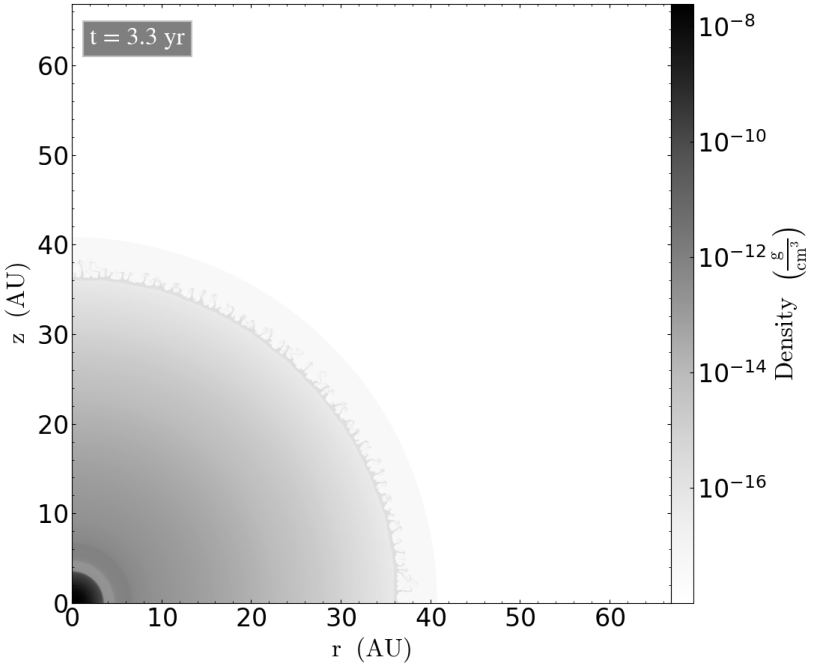

Figure 4 *Density plot of the CSM hydrodynamical models, showing Rayleigh–Taylor instabilities and a clear forward shock after the injected faster wind collides with previously ejected lower-density material. The swept-up ambient medium also produces a stratified shocked region at the reverse shock, feeding instabilities into the pre-SN environment.*

case of SN 1987A, with possible applications of my breakout model.

From these developments we outlined a plan for papers to be drafted in the coming months:

- **Paper I – RSG shock breakout:** a study of multidimensional effects, including shock structures, radiation precursors, and a comparison of progenitor stars and CSM profiles. The MGFLD method naturally separates short-wavelength emission from the forward shock and longer-wavelength components from radiation precursors. This will be the first MGFLD study of 2D RSG breakout.
- **Paper II – confined-shell CSM interaction:** the main collaborative project, focusing on confined-shell CSM relevant to many Type II SNe, where dense structures close to the progenitor may arise from violent mass eruptions or extended envelopes late in evolution. As shown in Fig. 4, the CSM formation simulations reproduce time-dependent mass-loss histories by injecting material at the inner boundary into an ambient medium of $10^{-18}\,\mathrm{g\,cm^{-3}}$, producing both forward and reverse shocks.
- **Paper III – link to later light curves:** an extension of the breakout work to Monte Carlo radiative transfer with detailed line profiles, providing a consistent picture from SBO to later-phase light curve evolution.

IV. Future Perspective

Building on the progress made during the NSTC–DAAD Summer Programme at HITS, I have applied for the NSTC–DAAD Sandwich Programme with the support

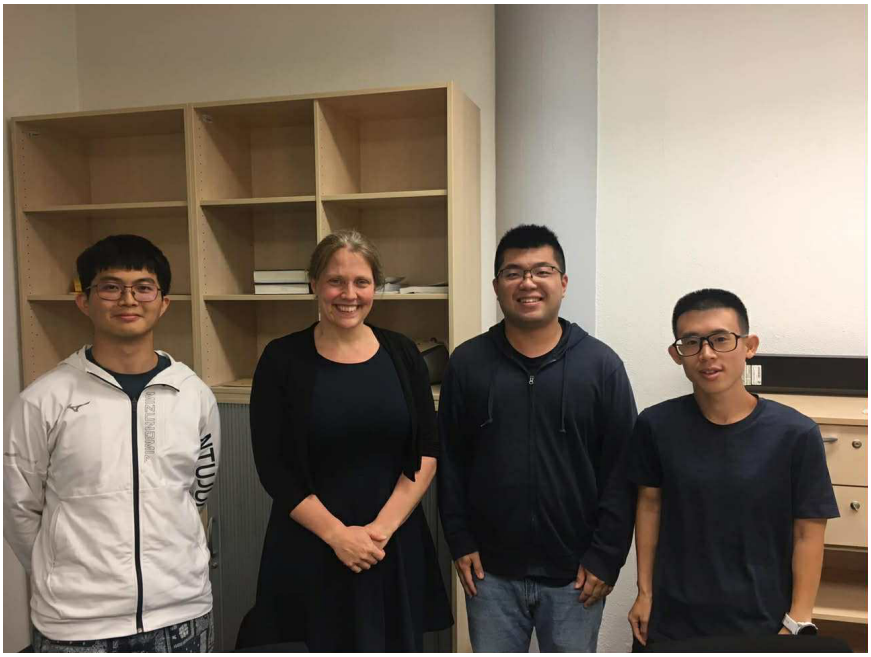

Figure 5 *I present the shock breakout studies and receive great reactions from the Munich research team. The director of Max Planck Astrophysics stellar astrophysics group, Prof. Dr. Selma E. de Mink.*

of Prof. Friedrich Röpke. The next stage will expand the summer work on multidimensional SBO into a broader investigation of CSM interaction, with the following objectives:

1. **Multidimensional SBO–CSM simulations with MGFLD:** carry out simulations with `CASTRO` on GPU-accelerated AMR grids, including both wind-driven and confined-shell CSM. These runs will capture angular and spectral effects and provide more realistic SBO predictions than 1D or gray 3D models.
2. **Integration with binary evolution models:** use binary and common-envelope models from the PSO group (e.g. Vetter et al. 2024; Wei et al. 2024) as inputs, to test how late-stage interaction shapes the CSM geometry and modifies breakout signatures.
3. **Synthetic observables and machine-learning emulators:** extend preliminary `SEDONA` calculations to produce light curves and spectra for comparison with early-time Type II SN observations. Machine learning will then be applied to generalize the results across parameter space.
4. **Scientific output and thesis integration:** produce at least one major paper on confined-shell SBO environments, complementing my ongoing work on SN 1987A (BSG) and RSG progenitors. Together these will form the main chapters of my Ph.D. thesis.

The Sandwich Programme also provides the framework for regular meetings, coordinated use of HPC resources in Germany, Taiwan, and the USA, and joint manuscript preparation with the PSO group. With these structures in place, the exploratory steps of this summer can be turned into concrete contributions to the study of shock breakout and its role in the final stages of massive star evolution.