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Core-Collapse Supernova Explosion Mechanism Studies on NIF

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1 Abstract

The first quarter work in the project was focused on developing a basis for in-depth analysis to be conducted later on. Initial work consisted of semi-analytic investigation of the Euler equations. In particular, we analyzed the one-dimensional, steady Euler equations in spherical geometry with no source terms. We found that in order to maintain physically admissible flow structures, the aspect ratio of the domain (i.e. relative thickness of the post-shock region) must be constrained to be relatively narrow ($r_{shock}/r_{inner} < 2$). In addition to the semi-analytic studies, the work on adapting the FLASH code for time-dependent numerical studies has started. Specifically, we designed and implemented the necessary boundary conditions. We also started code modifications required for investigating stability properties of the quasi-steady-state configurations.

The second quarter work on the project was focused on determining if a steady-state SASI scenario can exist in laboratory conditions. In order to obtain experimentally feasible solutions, the temperature in the domain should be on the order of 1×10^6 K, the shock should be relatively strong (Mach ≥ 3), and the Euler number in the post-shock must be compatible with the range of acceptable values based on theory and current simulations ($0.6 \leq Eu \leq 0.8$). Using these constraints as a starting point we were able to identify corresponding density, velocity, and pressure parameter ranges coupled with the geometric constraints obtained in Q1. Using these ranges, we generated steady, one-dimensional, and experimentally viable hydrodynamic models. These results show promise that steady SASI-type configurations are possible in the laboratory.

Additionally, code development continued by implementing the steady solver we used to generate these initial results for the FLASH code. This new module allows the code to initialize a multidimensional simulation to feasible steady-state values. More importantly, we verified that the code can successfully maintain stationary SASI configurations in multidimensions. This is prerequisite for planned stability studies of perturbed SASI scenarios.

In the third quarter of work we investigated the stability of the laboratory SASI scenario when subjected to perturbations upstream from the shock. In order to accomplish this, we first mapped the radial profiles obtained in Q2 into 1-D and 2-D spherical geometries onto the FLASH code mesh. We then introduced sinusoidal fluctuations in density at the

inflowing boundary. In one-dimension this is a simple sinusoid, but in two-dimensions appears as an “egg crate” pattern. Such a configuration was chosen to be compatible with possible target fabrications.

Using the parameter space determined in Q2, we added two additional parameters: the density perturbation amplitude, and the density perturbation frequency. The perturbation amplitude (peak to trough) varied from 0% to 25% of the nominal upstream value, and the perturbation frequency was chosen to fit between 1 and 20 wavelengths in the post-shock region. Scanning this updated parameter space showed that the shock’s oscillation frequency (in radial position) had a one-to-one correspondence to the perturbation frequency. This suggested that any perturbation induced development in the post-shock region flow structure did not communicate with the shock. That is, no outward traveling pressure waves were returning to the SASI shock front. Such a situation is hypothesized in the supernova setting, and is the basis for the theory of the advective acoustic cycle (or vertical acoustic cycle). Indeed, one-dimensional supernova simulations show that perturbations are allowed to accumulate due to the hydrostatic atmosphere, resulting in outward shocks interacting with the SASI shock. Visual analysis of the post-shock flow showed that sinusoidal perturbations in density are transformed into sinusoidal perturbations in the other primitive variables, which were then advected from the domain across the inner boundary.

The other result from the one-dimensional runs was in regard to the stationarity of the initial shock. Once the shock moved too far from its nominal position it would eventually collapse to, or drift away from, the inner boundary. It appeared that admissible steady shocks in spherical geometries lie at saddle points in the phase space, and minor deviations would eventually drive them away from equilibrium. This was not insurmountable, as we only required that the shock stay near equilibrium for “long enough” in order to study the relevant phenomena. Current SASI theory coupled with observations indicates that significant flow structure should develop within approximately 10 post-shock advective crossing times. For our purposes we considered a shock stationary until they traveled ±5% from their initial position. With this criterion, the one-dimensional results indicated that it was possible to obtain stationary shocks for up to 40 advective crossing times. This result was weakly anticorrelated to the post-shock aspect ratio.

Therefore, the one-dimensional results indicated that no post-shock features affect the SASI shock, but it was possible to generate configurations persisting long enough for hypothesized flow structures to develop.

From the set of one-dimensional models we chose a select group to run in two-dimensions. It was anticipated that multidimensional effects such as vorticity may cause an accumulation of post-shock material, enabling the expected SASI behavior. Our two-dimensional models did not produce such effects. The shock became deformed when the “egg crate” passes through, producing shear in the accreting material. This shearing produced vorticity, as expected, but did not cohere into a larger structure. As in one-dimension, any flow structure was advected from the domain without further interaction with the shock front.

In order to study a spherical, standing shock in the laboratory we determined that the aspect ratio of the post-shock domain must be narrow ($r_{shock}/r_{inner} < 2$). Combining this result with known HED constraints, we determined a feasible initial set of parameters to guide experimental designs. Of particular note is the relation between the temperature and velocity at the inner boundary. The relation has minimal dispersion and is nearly one-to-one. For experimentalists, this provides a good initial starting point, as the other primitive quantities are related to the inner temperature in a very definite, banded behavior.

We also determined that the flow structures obtainable in the laboratory do not coincide with those anticipated in the supernova setting. This occurs, essentially, due to the lack of a gravitational point source. Without this source, convectively unstable quasi-hydrostatic conditions are not readily available. The hydrostatic atmosphere in supernovae appears to be a fundamental catalyst for the accumulation of the fluid energy and subsequent acoustic perturbations the affect the shock evolution and lead to large scale asymmetries at later times.

2 Accomplishments in Q4

We spent the early part of Q4 attempting to modify entropy profiles in the post-shock region by adding a localized heating source. In the case of mild heating, it was possible to extend the admissible domain slightly, as the increased pressure would cause a stagnation in the Mach number over the heated region. The postshock flow remained stable in this case. Strong heating, as expected, resulted in point explosion-like behavior.

The last two months of Q4 were spent compiling the results and preparing the resulting paper for publication.

3 Project Conclusions

We conclude that although it is possible to create a spherical standing “accretion” shock in the high-energy density laser experiments on NIF, the system does not match characteristics of the exploding supernova system. In particular, laboratory systems of the type considered here do not produce the standing accretion shock instability. The reason for that is stable (entropy) profile of shocked gas. This situation is different in the supernova setting due to presence of gravity.

We have, however, been able to generate plasma configurations that were stable to perturbations and remained stationary for tens of advective times (hundreds of nanoseconds). Such configurations may have applications in studies of basic plasma properties, plasma hydrodynamics, and nuclear plasma physics effects, including situations relevant to Inertial Confinement Fusion.

4 Dissemination of Results

Project findings are presented in a paper by Timothy Handy and collaborators considered for publication in High Energy Density Physics journal. A copy of the submitted paper manuscript is attached to this report.

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