Discovering new dynamics of core-collapse supernova shock waves

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Abstract.
There is a growing body of evidence that core collapse supernova explosions are inherently asymmetric. The origin of this asymmetry may arise in the first few hundred milliseconds after core collapse when the nascent shock wave is susceptible to the spherical accretion shock instability, a dynamical instability discovered through computer simulations by the SciDAC-funded Terascale Supernova Initiative.

This work was followed up by large-scale 3D simulations enabled by the application of various high-performance computing technologies including networking and visualization. Recent 3D simulations have identified a vigorous non-axisymmetric mode of this supernova shock wave that can impart a significant amount of angular momentum to the underlying neutron star.

1. Introduction
Explosions of massive stars (core collapse supernovae) are arguably the most important link in our chain of origin beginning with the Big Bang and continuing through the formation and evolution of life on Earth. They are the dominant source of most elements in the Periodic Table between oxygen and iron, and are believed to be responsible for producing half of all elements heavier than iron. These explosions are some of the most energetic events in the Universe, give birth to neutron stars and stellar mass black holes, and serve as cosmic laboratories for particle and nuclear physics at extremes that are inaccessible in terrestrial experiment. For these and other reasons, core collapse supernova science has been an area of research traditionally supported by the Nuclear Physics and High Energy Physics Programs within the Office of Science, and now, under SciDAC, by the Office of Advanced Scientific Computing Research.

The modern theory for the origin of supernovae was first proposed in 1966 by Stirling Colgate and Richard White[1] working at the Lawrence Radiation Lab in Livermore. That seminal paper presented an extensive array of 1D hydrodynamic simulations to support the hypothesis that supernovae (the type we now call core collapse) are powered by the release of gravitational energy from the collapse of the core of a massive star. After nearly twenty years of study relying heavily on computation, the current paradigm of a stalled supernova shock revived by neutrino heating was born out of numerical simulations by Jim Wilson at Lawrence Livermore National Labs[2]. Supernova theory took another significant step forward in 1992 with the first two-dimensional simulations, discovering the importance of neutrino-driven convection behind the supernova shock[3]. Again this work was supported in part by the Department of Energy. This long history of supernova simulations supported at DOE labs continues today with the SciDAC-funded TSI effort led by Anthony Mezzacappa at Oak Ridge National Labs.
This strong dependence of supernova theory on computational physics is not surprising given the extreme physical conditions present in these events. Together with the Big Bang, core collapse supernovae (and related objects like collapsars) are perhaps unique in their critical dependence on all four fundamental forces of nature. This is a truly multi-physics problem. The extreme compactness of the collapsed core means that general relativistic effects can be important in determining the outcome of the collapse. The extreme densities of the core push our limits of understanding of the strong nuclear force and the state of matter at super-nuclear densities. The extreme flux of neutrinos from the core implies that a successful explosion depends critically on the weak nuclear force describing the interaction of the escaping neutrinos with the infalling star. Other processes such as the magneto-rotational instability may play an equally important role in supernovae. The complexity of core collapse supernovae demands a multi-faceted, coordinated research program like those supported by the SciDAC Program.

To illustrate the role of high performance computing in supernova research, we focus here on only one aspect of the problem: the dynamics of the nascent supernova shock wave shortly after the bounce of the imploded stellar core. This post-bounce accretion phase of core collapse supernovae is characterized by a standing accretion shock at a radius of a few hundred kilometers. The shock maintains a roughly constant radius during this epoch due to a balance between the ram pressure of the outer core falling into the shock at near free-fall velocity, and the high thermal pressure inside the spherical cavity defined by the shock. It is during this epoch when neutrino-driven convection may alter the dynamics and aid in driving an explosion[3, 4].

TSI began to investigate the dynamics of this post-bounce accretion shock based on the first generation of 2D supernova models[3, 5, 6, 7, 8]. All of these models exhibited some level of thermal convection, as predicted by the negative entropy gradients computed in one-dimensional simulations. However, there appeared to be more going on at late times when the accretion shock became significantly distorted from the original spherical shape. With the break from spherical symmetry, the radially infalling outer core would strike the shock at a slightly oblique angle, leading to strong non-radial flow behind the shock. Moreover, several of these models exhibited a tendency to develop low-order modes whereas the convection was originally present at significantly higher wave numbers. Was this low-order asymmetry driven by convection, or was something else affecting the flow?

The possible origin of a large-scale asymmetry in the supernova shock wave has taken on increased importance in recent years as observations of polarized light from supernovae have implied an asymmetric shock at the time it breaks free of the star[9]. Evidence of large asymmetries in the supernova shock may also be imprinted on the chemical composition, structure and dynamics of the expelled stellar ejecta, now observable by modern X-ray observations of young supernova remnants. Explosion asymmetries may also impart significant linear and angular momentum to the neutron stars left behind. A significant fraction of neutron stars are moving through space faster than the stellar population from which they were born, implying that the supernova event somehow imparted a significant kick. In addition, statistics of radio pulsars imply that most neutron stars were born with a spin period in the range of 10-50 milliseconds. While this might be explained by rotation of the progenitor star, recent stellar models suggest that the rotation of cores of massive stars slow dramatically with the age of the star, leaving behind a relatively slowly rotating core[10]. Why then are pulsars seen to spin so rapidly? To answer some of these questions we have used a dynamical model of the post-bounce accretion shock to explore sources of asymmetry in core collapse supernovae. In the following section we describe the physical model and how 2D simulations based on this model were used to discover the spherical accretion shock instability, or SASI. We then discuss the challenges we faced in moving this simulation work to large-scale three-dimensional simulations, and the subsequent discovery of a non-axisymmetric mode of the SASI leading to spin up of the underlying accreting neutron star.
2. Modeling the Post-Bounce Shock

The post-bounce phase is described by a standing accretion shock with outer core material raining down on the shock at roughly half the free-fall velocity. After traversing the shock, this gas decelerates and gradually settles onto the surface of the nascent neutron star. The pressure of this post-shock gas is dominated by electron-positron pairs and radiation, and as such can be modeled as a $\gamma = 4/3$ gas. The approximation of an hydrostatic atmosphere immediately below the accretion shock then yields the result that the gas density increases as $r^{-3}$ and the gas pressure increases as $r^{-4}$ with decreasing radius behind the shock. Deeper within this settling region, the gas pressure becomes dominated by non-relativistic nucleons and the temperature becomes roughly constant due to neutrino emission. The flow below this transition radius can thus be approximated by an isothermal hydrostatic atmosphere. The steady nature of this accretion shock and post-shock settling solution is maintained by a balance between fresh matter accreting through the standing shock, and dense matter cooling via neutrinos and condensing onto the surface of the nascent neutron star [11, 12].

We have developed a model of this standing accretion shock based on the assumption of an ideal gas with $\gamma = 4/3$ and an optically thin cooling function that mimics the neutrino losses from the vicinity of the neutrino sphere. By assuming a steady flow, all of the shocked gas must have passed through the same accretion shock and hence was raised to the same value of entropy. Initially this gas is roughly adiabatic (the cooling function is only important near the surface of the accreting core), and it flows inwards from the shock with a constant value of entropy. Only when it approaches the surface does the cooling become important and the local entropy decreases. The result is a positive entropy gradient (stable to convection) deep in the post-shock accretion flow, and a zero entropy gradient (marginally stable) closer to the standing shock. There is no convection in this model. This feature allows us to study the dynamics of the shock independent of any post-shock convection.

We use the time-dependent hydrodynamics code VH-1 (http://astro.physics.ncsu.edu/pub/VH-1/) to study the dynamical behavior of this post-bounce shock model. Details of this numerical implementation of the model, including the use of dissipation to maintain a smooth flow in the absence of any perturbations, are provided in Blondin, Mezzacappa and DeMarino[13].

![Figure 1](image-url) Figure 1. The time evolution of the SASI, driving a steady, spherical accretion shock into an oscillating, aspherical shock. The shading depicts variations in gas entropy, and each image is separated in time by roughly 22 ms (evolving from left to right).

2.1. SASI Discovery

One of the initial discoveries through computing within TSI was the SASI - a global instability of the post-bounce supernova shock that may impart large asymmetries to the supernova and
possibly aid in driving the explosion[13]. An example of the evolution of the SASI is show in Fig. 1, where an initially steady-state, spherically-symmetric accretion shock becomes highly aspherical after only a few flow crossing times. In the linear regime the accretion shock behaves like a resonant cavity, with standing pressure waves filling the interior. The longest wavelength modes are seen to grow exponentially, and eventually the shock front is distorted by a dominant 'sloshing mode' characterized by a spherical harmonic of \( l = 1 \). Once the spherical symmetry of the accretion shock is broken, the post shock flow is no longer radially inward. This non-radial flow continues to drive the sloshing mode to larger and larger amplitudes, resulting in an increasingly larger shock radius.

The origin of the SASI can be traced to the response of the post-shock pressure to changes in the shock radius[17]. If the pressure in one hemisphere becomes slightly higher than equilibrium, it will push the spherical accretion shock outwards. Because the preshock ram pressure drops with increasing radius (as \( r^{-2.5} \)), the outward shock displacement leads to a smaller pressure immediately behind the shock. However, given that the postshock pressure increases with decreasing radius as \( r^{-4} \), the postshock pressure for the perturbed shock will be greater than the postshock pressure for the unperturbed shock at each radius below the radius of the original unperturbed shock: The \( r^{-4} \) increase trumps the \( r^{-2.5} \) decrease. This provides for a positive feedback on the pressure of a standing acoustic wave. Imagine a flute whose sound amplified by a factor of \( e \) with each oscillation of the trapped sound wave.

The presence of the SASI implies that, as long as core collapse supernovae evolve through a phase with a quasi-steady shock as seen in present-day models, the supernova shock wave will be inherently asymmetric. Moreover, the SASI leads to a shock growing out of the stellar core with a low-order asymmetry, consistent with spectropolarimetry data of young supernovae (after the shock has broken out of the star).

While these results are very exciting, we note that because the SASI is a global instability with perturbations flowing along the symmetry axis, one could imagine that in three dimensions the dominant \( l = 1 \) mode might not remain coherent. Through this initial work it became clear that three-dimensional simulations would be needed to understand the true dynamics of a young supernova shock wave.

2.2. Code Verification
An important contribution of this analytic model is the ability to quantitatively validate the time-dependent hydrodynamics codes used in core-collapse simulations. While most such codes used in the astrophysics community are tested against standard problems[14], it is important that generic hydrodynamics codes be validated against test problems that are as close as possible to the problem being studied[15]. The linear stability analysis of spherical accretion shocks performed by Houck and Chevalier[16] provides a valuable test problem for supernova simulation codes. Their model is very similar to the supernova model defined herein. Any one-dimensional supernova code should be able to reproduce the complex growth rates of radial modes computed from their linear stability analysis.

Blondin and Mezzacappa[17] ran one-dimensional hydrodynamic simulations of the Houck and Chevalier model and measured the real and imaginary parts of the complex growth rates, the results of which are reproduced in Fig. 2. The agreement with the linear stability analysis is remarkable. For standing accretion shocks with a radius less than about 20 times the radius of the underlying accreting star, the shock is stable to radial perturbations. While shocks with a large stand-off distance are unstable, this regime does not apply to the core-collapse supernova problem.

Unfortunately, Houck and Chevalier[16] did not publish any results for non-radial modes of their fall-back model, and so this approach cannot (yet) be used to validate the two-dimensional time-dependent hydrodynamic codes. In the absence of an analytic model for validation, we
can turn to a comparison of different numerical codes. Ud-Doula and Blondin [18] present results from 2D simulations of the SASI using two different hydrodynamics codes: ZEUS and VH-1. Despite significant differences in the algorithms of these codes (VH-1 uses a Riemann solver following the PPMLR scheme [19] while ZEUS [20] uses an artificial viscosity to generate the requisite entropy at the accretion shock), the evolution of the SASI is strikingly similar.

3. Moving to Tera-Scale Simulations

Conceptually, computing a three-dimensional simulation of the SASI is a small step from the two-dimensional simulations described above. In practice, however, scaling the simulation size from gigabytes to terabytes has proven problematic. By examining the workflow of this scientific investigation, one can identify the technical challenges faced in moving from the initial 2D simulations to the required 3D simulations.

3.1. Technical Challenges

- **Simulation code.** In general, moving a computational project forward involves substantial development of the underlying simulation code(s). For this particular application, however, extending the code from the initial 2D simulations to large-scale 3D simulations was relatively trivial.

- **Floating point operations.** In moving from a 2D simulation using 100,000 zones to a 3D simulation using a billion zones, we are stepping up in required flops by a factor of 10,000. Fortunately, the necessary computing power needed to make this transition was provided by the DOE through large parallel platforms such as the IBM SP at NERSC and the Cray X1 at NCCS. Accessibility to such capability resources is paramount to continued success in supernova research.

- **Data output.** The amount of data is increasing from gigabytes to terabytes, while the number of processors writing to a shared file system is increasing from 10’s to 100’s or 1000’s. We have chosen a trivial route for output from a large number of parallel processors, namely a separate output from each parallel task. This leaves more work for post-processing, but...
allows our codes to remain more transportable. This approach will likely change as parallel data interfaces become more mature and wide-spread.

- **Data transport** Moving a GB of data across the country is manageable with current network infrastructure and protocols. Moving a TB of data is not.

- **Visualization and analysis** A full set of data at one fixed time from a 2D simulation fits comfortably inside the 2GB memory limit of a typical workstation. A comparable data set from a 3D simulation can reach 20 GB in size. One cannot expect a single computer to be able to digest a data set that took 500 processors to create. New approaches in parallel visualization and analysis must be employed at this scale of terabyte data.

For this project in particular, the primary challenges all arise from the enormity of the data sets. Generating terabytes of data is easy; Extracting meaningful science from that data is hard.

### 3.2. Key Enabling Technologies

The TSI investigation of the SASI continues to benefit from a large number of collaborations originating through SciDAC. These include assistance in implementing various system tools such as PVFS2, parallel netCDF, bbcp and other file transfer tools, development of tools to aid in automating the simulation workflow, and much-needed help in visualizing 3D data sets.

However, two key technologies helped bridge the gap between data and scientist, truly enabling the scientific discovery process: LoRS tools for data transport (http://loci.cs.utk.edu), and EnSight for parallel visualization (http://www.ceintl.com). These are certainly not the only tools for the job at hand, but by providing a solution that was easy to deploy, use, and adapt, these two technologies became essential to the TSI workflow.

When data transfer rates from NERSC to NC State prohibited the movement of data, Micah Beck’s Logistical Computing and Internetworking group provided a simple, ready-to-use solution. After a quick and relatively easy installation of their LoRS tools, we were able to move data to and from the Logistical Network at 10 to 20 times the rate at which we had been moving data between CCS and NC State, and even larger improvements when moving data across the country.

In hindsight the LoRS software was much more valuable than a simple file transfer tool. Given the large, collaborative nature of TSI, and in particular the direct involvement of several research groups in scientific visualization, we found that the Logistical Network was an ideal way to temporarily store and share our terascale data sets with researchers around the country.

The combination of EnSight software and a commodity linux cluster allowed us to finally view our simulation data with reasonable interactivity. With data dispersed onto the local disks of the cluster nodes, the EnSight servers can read even a 10GB data set in a matter of seconds. Moreover, this approach is by far the most economical way to create a computer with the more than 40 GB of memory needed to visualize such a data set. The EnSight software comes with the advantages and disadvantages of a commercial product...

While EnSight has proven invaluable to this project, the challenge of visualizing such large 3D data sets is an active area of research in and of itself, and well beyond the scope of a typical application scientist. This project has benefited greatly from collaborations with researchers in scientific visualization across the county, including Kwan-Liu Ma (UC Davis), Pat McCormick (LANL), Jian Huang (UTK) and Christopher Healey (NC State). These groups are developing new techniques for extracting meaningful science out of large 4D data sets. The results are nothing short of amazing, but they have not yet been incorporated into the mainstream production work. The next crucial step is to package these tools into something that can be easily handled by the application scientist so that they can become part of the scientific discovery process.
Figure 3. A volume rendering by K.-L. Ma (UCD) of the gas entropy illustrating the growth of the SASI in a three-dimensional simulation. Understanding the dynamics of these simulations relies on the ability to view all (or most) of the simulation domain, but extracting only a select few features at a time.

3.3. Evolving Data Flow
Much of the logistical work required to move the tera-scale simulations to production level involved (and continues to involve) the flow of data from the supercomputer on which it was created to the individual disks of the analysis cluster on which it is visualized and studied. The former is provided by the high quality supercomputer centers like NERSC and NCCS, while the latter is provided by a commodity linux cluster and parallel visualization software like EnSight. Filling in the middle to produce an end-to-end solution for terascale simulations is an ongoing process.

It is important to note that these two end machines play significantly different roles that are not likely to be played by the same machine. In particular the analysis cluster must be used interactively to allow the type of query-based visualization and analysis necessary for scientific discovery. Note, however, that these two machines could share the same file system, alleviating the need for any disk-to-disk movement of the data.

Our current simulations create a single large (10's of GB) data file in netCDF format on the shared file system at a given instance of time in the model evolution. Storing a few hundred time steps then generates several TB of data. In our current mode of operation each of the MPI tasks in the simulation writes an independent file to disk, and a post-processing program then merges the parallel files into a the single netCDF file. Implementation of the parallel netCDF interface will remove this post-processing step (provided it is efficient). The data is then moved over the network, both to an archive facility like HPSS and to the analysis cluster. Once on the shared file system of the cluster, the data is partitioned and distributed to the local disks of the cluster nodes, where it resides for weeks or months while it is studied.

There is much room for improvement in this process, from implementing a parallel file
interface on both ends of the data flow and improving performance of the parallel file system on the commodity cluster, to using parallel sends and receives over a high-bandwidth network. As an example of ongoing research in this arena, Jonghyun Lee (ANL) is developing an MPI-IO interface to the Logistical Networking tools. This opens up the possibility of moving files into and out of the Logistical Network directly from our simulation code and visualization software without significant new code development.

4. Scientific Discovery through Advanced Computing

The importance of working with computer scientists to implement these networking and visualization tools was exemplified by the TSI discovery of strong rotational flow generated by the SASI in three-dimensional simulations. When these 3D simulations were first moved to the Cray X1 at NCCS, this machine was not yet in production mode and we did not have an efficient method for moving data off the machine. Instead, we forged ahead with the largest 3D supernova simulations done to that date, but keeping only global diagnostics computed on the fly. From this first large-scale 3D run we saw that the nonlinear evolution of the SASI lead to a very large accretion rate of angular momentum onto the proto-neutron star. But without access to the full data, we could not identify the physical mechanism for this exciting result. We knew there was valuable science to be learned from these simulations, but without the tools for discovery we were left with idle speculation.

Figure 4. The clockwise propagation of an $m = 1$ mode of the accretion shock around the proto-neutron star is illustrated in this time sequence showing slices through the equatorial plane. The shading depicts gas entropy, with black representing high values and white representing low values.

Working with network researchers at ORNL, we began using bbcp to efficiently move data from NCCS to NC State. Eventually we were also able to use the LoRS tools to quickly move data off the Cray X1. With the data eventually distributed on the nodes of our local linux cluster, we could finally push forward with the interactive query of the data necessary for scientific discovery.

What we found was a surprise to everyone. As initially feared (but now embraced!), the $l = 1$ mode of the SASI did not survive long in the nonlinear phase in 3D. The growing sloshing of the supernova shock wave along the symmetry axis in 2D gave way to an $m = 1$ spiral mode in 3D. In essence, once the amplitude of the sloshing mode became sufficiently large, it was not able to maintain an axis through the center of the star. Once the axisymmetry was broken, the shock began to propagate around the proto-neutron star as shown in Figure 4. This sequence of
images shows the extended shock moving clockwise around the proto-neutron star, rolling over and subverting the shock ahead of the perturbation. The diverted flow (seen as low-entropy gas in Figure 4) from the shock ahead of the spiraling wave is deflected towards the interior proto-neutron star in such a way as to drive a strong counter-clockwise flow close to the accreting star. This counter-rotating flow (relative to the spiraling shock) is illustrated by 3D streamlines in Figure 5.

The consequences of this discovery may have a significant impact on our understanding of core collapse supernovae, although we acknowledge that much more work must be done to understand this phenomenon and its role in supernovae. This work clearly shows, however, that it is possible for the core collapse of a spherically-symmetric, non-rotating massive star to generate an asymmetric supernova explosion and leave behind a rapidly-rotating neutron star with a period in the range of 10’s of milliseconds. Moreover, the strong rotational flow generated by this non-axisymmetric mode of the SASI is likely to change our understanding of the role of magnetic fields in core collapse supernovae. No longer is the presence of the MRI dependent on a rapidly-rotating progenitor star - the SASI itself may provide the necessary rotation to make magnetic fields dynamically important.

Figure 5. Streamlines illustrate the formation of a rotational flow around the accreting neutron star in a 3D SASI simulation.

5. Moving to Peta-Scale Simulations
This work clearly demonstrates that the full range of shock dynamics in core collapse supernovae is only accessible through full three-dimensional simulations. Moreover, the ubiquity of non-axisymmetric modes in these simulations suggests that three-dimensional simulations may be essential to understanding the true nature of these extreme events. This simple conclusion carries dramatic consequences regarding the future path of numerical simulations of core collapse supernovae.

Current state-of-the-art 2D supernova simulations that include full 2D neutrino transport and the most up-to-date nuclear physics use a comparable total number of flops to the 3D hydrodynamic simulation presented here but produce a modest 70 GB of data using a $256^2$ grid. To reach the goal of extending such models to full 3D will require true petaflop computing.
platforms as well as the ability to manage (read/write, transport, visualize, analyze, archive) petabyte data sets.

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6. References
[1] S. A. Colgate and R. H. White 1966, *Astroph. J.*, 143, 626
[2] H. A. Bethe and J. R. Wilson 1985, *Astroph. J.*, 295, 14-23
[3] M. Herant, W. Benz and S. A. Colgate 1992, *Astroph. J.*, 395, 642
[4] M. Herant et al. 1994, *Astroph. J.*, 435, 339
[5] D. S. Miller, J. R. Wilson and R. W. Mayle 1993, *Astroph. J.*, 415, 278
[6] A. Burrows, J. Hayes and B. A. Fryxell 1995, *Astroph. J.*, 450, 830
[7] H.-Th. Janka and E. Müller 1996, *Astron. and Astroph.*, 296, 167
[8] A. Mezzacappa et al. 1998, *Astroph. J.*, 495, 911
[9] L. Wang, D. A. Howell, P. Höflich and J. C. Wheeler 2001, *Astroph. J.*, 550, 1030
[10] A. Heger, S. E. Woosley, H. C. Spruit 2005, *Astroph. J.*, 626, 350
[11] R. A. Chevalier 1989, *Astroph. J.*, 346, 847
[12] H.-T. Janka 2001, *Astron. and Astroph.*, 368, 527
[13] J. M. Blondin, A. Mezzacappa and C. DeMarino 2003, *Astroph. J.*, 584, 971
[14] J. M. Stone et al. 1992, *Astroph. J.*, 388, 415
[15] A. C. Calder et al. 2002, *Astroph. J. Suppl.*, 143, 201
[16] J. C. Houck and R. A. Chevalier 1992, *Astroph. J.*, 395, 592
[17] J. M. Blondin and A. Mezzacappa 2005, *Astroph. J.*, submitted
[18] A. ud-Doula and J. M. Blondin 2005, *Astroph. J.*, submitted
[19] P. Colella and P. R. Woodward 1984, *J. Comput. Phys.*, 54, 174
[20] J. M. Stone and M. L. Norman 1992, *Astroph. J. Suppl.*, 80, 753