Core-Collapse Supernova Explosion Mechanisms

Timothy Handy[1], Tomasz Plewa[1], Andrzej Odrzywolek[2]

(1) Florida State University, (2) Jagiellonian University

Abstract

Despite advances in theory and computer models, the explosion mechanisms in core collapse supernovae (ccSN) are still under debate. In particular, the reported relative importance of the standing accretion shock instability (SASI), non-SASI turbulent fluctuations, and bulk convective motion due to neutrino heating varies between research groups, with no current consensus. In this work we offer our own insight into the problem, utilizing an extensive database of 2D and 3D ccSN models tuned to match the energetics of SN 1987A. We propose, implement, and apply novel methods for characterizing the post-bounce evolution of the stellar core. Our analysis focuses on energy transport, convection, morphology of the flow, and statistical properties of fluid motions. We compare the results of our work to those reported by other groups. In particular, we find that our models indicate more vigorous explosions in 3D as compared to 2D for the same neutrino luminosity.

Core-Collapse Supernova Explosions

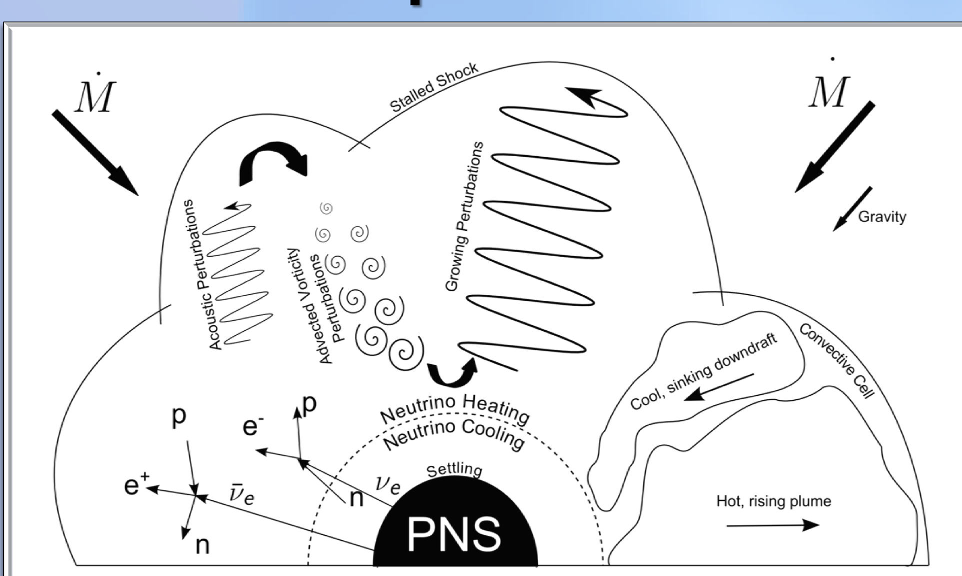

Figure 1: Illustration of various physics processes in the pre-explosion supernova core.

There persists a large number of diverse opinions regarding the nature of exploding, massive stars. Currently, the accepted elements of the explosion process are gravitational collapse of the stellar core and neutrino emission from the proto-neutron star (PNS). Combined with hydrodynamics, these processes constitute the key elements of the explosion scenario. The explosion itself is the result of the contribution and interaction between these processes and their exact nature is only approximately known. Furthermore, new physics processes emerge in multi-dimensions (neutrino-driven convection, the advective-acoustic cycle, and turbulence). This prompts the following questions:

- Is there a change in the critical neutrino luminosity required for the explosion when moving from two dimensions to three dimensions?
- In multidimensional situations, what are the contributions from participating processes?

In this work we offer our own insights into the problem by modeling a core-collapse supernova explosion tuned to the energetics of supernova SN 1987A. By attempting to connect model observables to observations, we hope to distinguish between relevant physics processes crucial to the explosion, and those that only nominally participate in the evolution.

Model

All simulations were performed using the HOTB code. HOTB is a multidimensional, moving mesh, finite volume code. It maintains the ability to perform approximate neutrino transport ("light bulb" model), self-gravitation, and complex equation of state. All simulations were performed in spherical geometry with 450 radial zones and 2 degree angular resolution.

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &+ \nabla\cdot(\rho\vec{u}) &&= 0\\
\frac{\partial \rho\vec{u}}{\partial t} &+ \nabla\cdot(\rho\vec{u}\otimes\vec{u}) &&= -\nabla P - \rho\nabla\Phi + \vec{Q}_M\\
\frac{\partial \rho E}{\partial t} &+ \nabla\cdot[\vec{u}(\rho E + P)] &&= -\rho\vec{u}\cdot\nabla\Phi + Q_E + \vec{u}\cdot\vec{Q}_M\\
\frac{\partial \rho Y_e}{\partial t} &+ \nabla\cdot(\rho Y_e\vec{u}) &&= Q_N
\end{aligned}
$$

Our progenitor is the 15 solar mass star of Woosley et al. [7] The only free parameter in this study is the neutrino luminosity from the PNS (via the light bulb approximation). The bulk of our models are computed with "slow" contracting PNSs (scPNS). For the sake of completeness, we compute some models with fast contracting PNSs (fcPNS). The progenitor model is randomly perturbed for each simulation, allowing for differing energetics for a fixed neutrino luminosity. Gravity is computed by treating the proto-neutron star as a point-mass (excised from the computational domain) with a correction for self-gravity of the material on the grid.

Dimensionality Effects

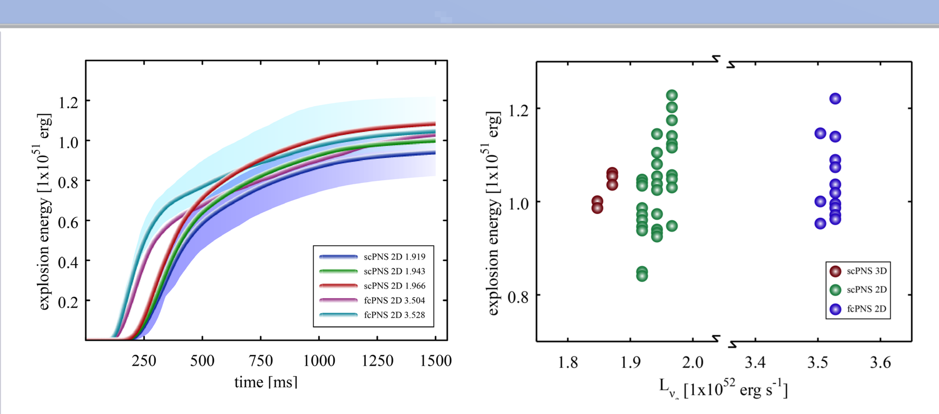

Figure 2: (left panel) Explosion energy over time. Hatch marks are provided on the extreme luminosity models to illustrate the sensitivity of the explosion energy to random initial perturbations. Note that the fast contracting PNS models explode significantly quicker.
(right panel) Explosion energy as a function of parameterized neutrino luminosity at 1.5s. There appears to be a systematic decrease, when going from 2d to 3d, in the amount of driving luminosity required to achieve equivalently energetic explosions. The fast contracting PNS models require nearly double the driving luminosity to reach SN 1987A energetics.

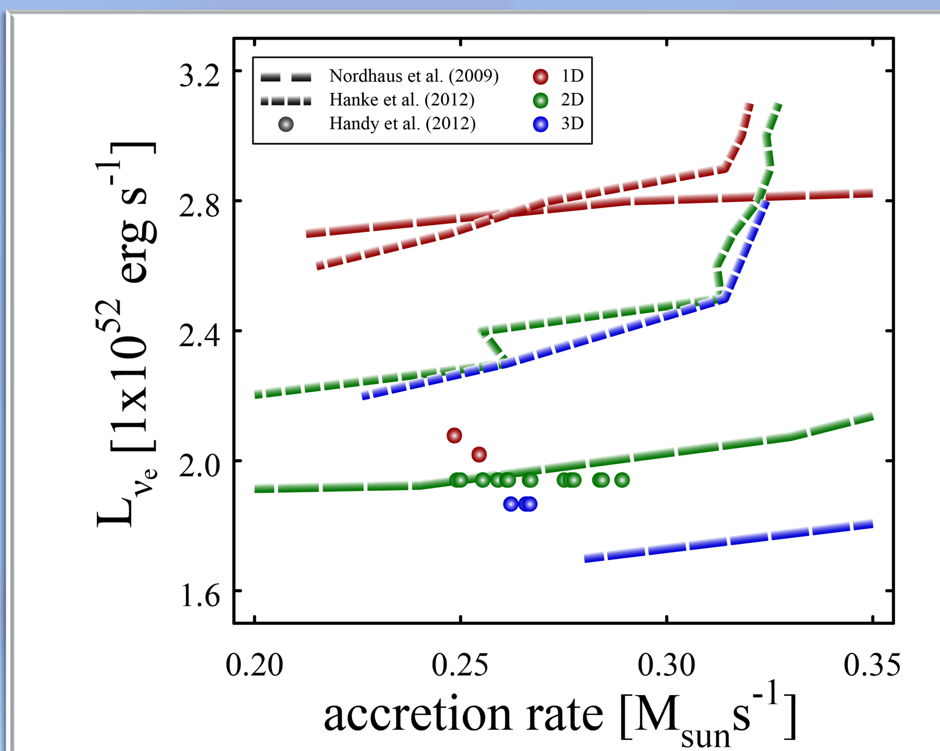

Figure 3: Critical luminosity curves for Nordhaus et al. [6], Hanke et al. [2], and the current work. Note that the results from other groups are not tuned to a specific explosion energy, and are in fact quite dim explosions. If a luminosity lies above a given curve, then the star should successfully explode. We note that there are large discrepancies between groups.

Advective-Acoustic Cycle

The advective-acoustic cycle is a well developed theory (Foglizzo [1]), which is expected to manifest itself in ccSNe as the standing accretion shock instability. The characteristic of this event is a side-to-side "sloshing", causing the low-order modes of the shock front to periodically oscillate at early times. This process is thought to be a trigger for convection by keeping material in the neutrino heating region.

$$a_l = \int_\Omega Y_{l0}^* R_s \, d\Omega$$

$$Y_{lm} = P_l^m(\cos\theta)e^{im\phi}$$

R_s: shock radius

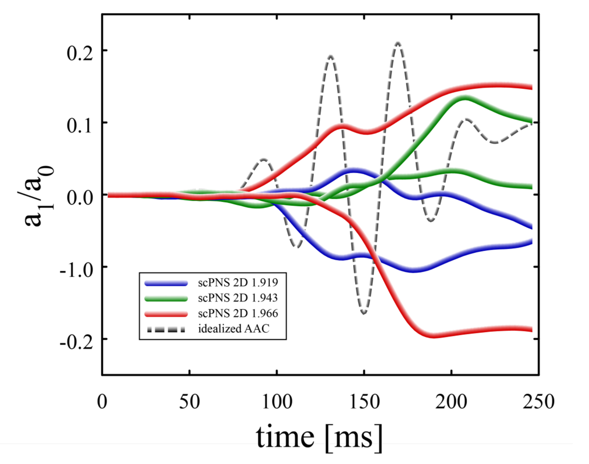

Figure 4: L=1 spherical harmonic mode of the shock radius normalized by the nominal shock radius. Shown are a subset of results from the 2D, slow contracting PNS models. A prototypical example of the AAC operating is plotted as well for comparison.

Neutrino-Driven Convection

Convection occurs when material becomes buoyant against gravity (typically by heating). This warm material rises, cools, and then sinks. This forms a convective cell, wherein material can be repeatedly reheated, potentially unbinding it from the star's gravity.

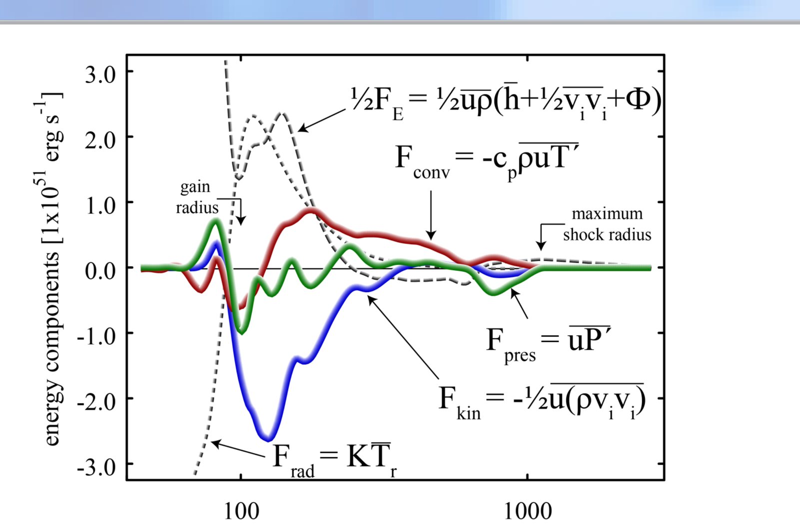

Figure 5: Partial energy decomposition for a characteristic 2D model at the time of explosion (200ms). Note that only the components which directly correspond to the classic case of penetrative convection are shown.

Reynolds Stresses

Murphy et al. [5] recently proposed that Reynolds stresses behind the shock may drive the shock to higher radii. This would also allow material to be heated longer by neutrinos.

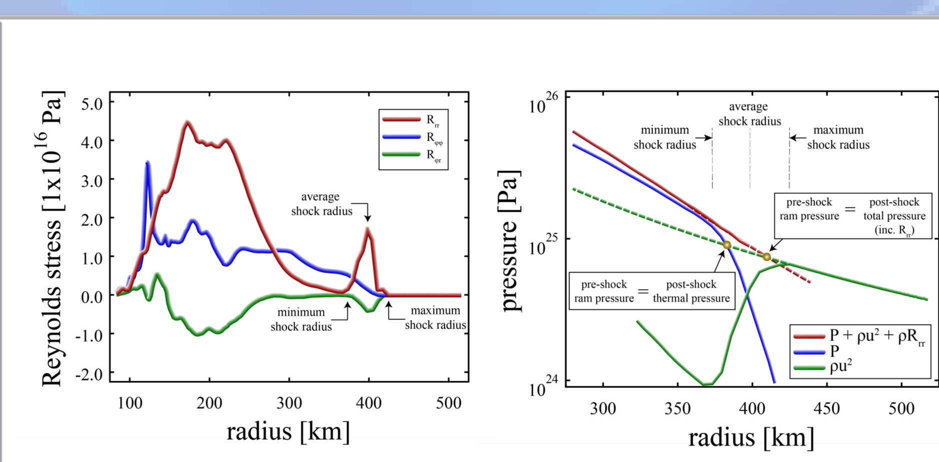

Figure 6: (left panel) Reynolds stress components for the same nominal model as in Fig. 5 (at 100ms). (right panel) Investigation of the contributions from the radial Reynolds stress to the nominal shock position, as proposed by Murphy et al. [5] Note that the correction utilizing R_{rr} still lies within the maximum extent of the shock, casting doubt on the importance Reynolds stresses in these models.

Magnetic Field Effects

$$\frac{\partial \vec{B}}{\partial t} = \frac{ck_b}{e}\nabla T_e \times \nabla n_e$$

Fryxell et al. [8] estimated that the magnetic fields produced during the late-time explosion phase (as the shock moves through the lighter envelopes) are weak (≈1 G).

However, the convective process operating prior to shock revival may generate significantly stronger fields. The evolution of the pre-explosion convection occurs on a hydrostatic background, with density gradients pointing predominantly outward, while temperature gradients are oriented across the bubble surface in the angular direction. Self-generation of magnetic fields would be induced by this misalignment of temperature and density gradients, with the possibility of efficient Biermann battery operation. In addition, non-uniform heating and chaotic motions near the gain radius may also create favorable conditions.

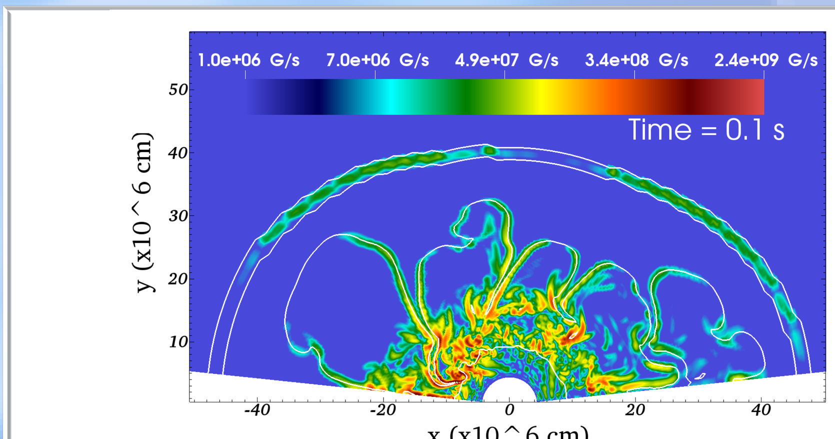

Figure 7: Biermann battery source term. Outer white contour denote the supernova shock. Inner white contours show the outlines of buoyant, convective bubbles. Self-generation of magnetic fields occurs near the interfaces of the bubbles and down-flows, and in the chaotic region above the gain radius.

Conclusions

From our study of core-collapse supernova tuned to the energetics of SN 1987A, we find a systematic decrease of the required neutrino luminosity when the dimensionality of the problem increases. While we do not find as strong of a correlation as Nordhaus et al. [6] or Hanke et al. [2] when moving from one dimension to two dimensions, our models provide evidence for this trend to continue from two dimensions to three dimensions. This is contrary to Hanke et al.'s findings who do not find 3D models exploding at lower neutrino luminosities. Our result stays in qualitative agreement with the work of Norhaus et al., although the effect is much smaller (about 3% compared to 12% reported by Nordhaus et al.). We note that both of these groups used a different 15 solar mass progenitor, which may contribute to the differences. Additionally, the other studies are based on single realizations of models and do not take into account natural variations due to model nonlinearity. Finally, comparison between our work and the work of the above groups comes with the caveat that we only consider robust, energetic explosions, which might be characterized by a different relation between the critical neutrino luminosity and the accretion rate.

We do not see evidence of a participating advective-acoustic cycle (AAC) in our energetic explosion models. While much of the work on the AAC has been theoretical (cf. Foglizzo [1]), numerical evidence for its existence has been recently demonstrated by Mueller et al. [4], who found that emergence of an active AAC stems from long-term suppression of convection. However, our models develop vigorous convection and our energy budget appears to be dominated primarily by convective energy transport.

Examining our Reynolds stress data in the context proposed by Murphy et al. [5] shows that, in agreement with their theory, the nominal shock position is increased when including contributions from R_{rr}. However, the new, turbulence-aided mean position of the shock remains smaller than the actual maximum shock position. (Murphy et al.'s work does not explain how one accounts for asphericities of the shock in their theory.) Therefore, we find that chaotic motions behind the shock are not a primary driver of the shock.

We conclude that neutrino-driven convection is the primary driver behind energetic supernova explosions of progenitors of moderate masses such as that of SN 1987A. The results suggest that neutrino-driven convection can successfully power explosions operating without significant contributions from either AAC/SASI instabilities or turbulence. In addition, our initial estimates show that magnetic fields are unlikely to effect the hydrodynamic evolution of the system. However, the self-generated fields may be amplified by turbulence and dynamo effects, requiring full MHD simulations to address.

Acknowledgements

This research was supported by the NSF grant AST-1109113 and used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Dept. of Energy under Contract No. DE-AC02-05CH11123.

References

1. Foglizzo, T. ApJ 2009, 694:833
2. Hanke, F., Marek, A., Mueller, B., Janka, H-T. ApJ 2012, 755:138
3. Hurlburt, N.E., Toomre, J., Massaguer, J.M. ApJ 1986, 311:563
4. Mueller, B., Janka, H-T., Heger, A. arXiv:1205.7078v1
5. Murphy, J.W, Dolence, J.C., Burrows, A. arXiv:1205.3491v1
6. Nordhaus, J., Burrows, A., Almgren, A., Bell, J. ApJ 2012, 720:694
7. Woosley, S.E, Weaver, T.A. ApJS 1995, 101:181
8. Fryxell, B, et al., HEDP 2010, 6:162