The Character of Three-Dimensional Core-Collapse Simulation Results

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Abstract. We here in graphical form highlight some of the early phases in the explosion of core-collapse supernovae and the birth of neutron stars. The graphics presented summarizes the results of the almost fifty three-dimensional radiation/hydrodynamic simulations the Princeton group has simulated during the last three years using its state-of-the-art (though still evolving and improving) code Fornax.

1 Introduction

The core-collapse supernova problem has been a multi-physics challenge in theoretical astrophysics for more than 60 years. Its theoretical study lies at the confluence of nuclear, particle, neutrino, statistical, and gravitational physics and has persistently necessitated, as a consequence of intrinsic instabilities and multi-dimensional effects, the use of state-of-the-art computational resources. In fact, theoretical progress has paralleled the evolution of high-performance computing, as well as the gradual maturation of our understanding of the neutrino and of neutrino-matter interactions [1]. Moreover, since the explosion is inaugurated in the dense core of a massive star, its initial development is shrouded in mystery by the profound opacity of the star to photons. Hence, the traditional synergy between theory and observation that characterizes much of astronomy is often denied us and we are forced to connect data and theory at least one step removed from direct (however remote) experience. Nevertheless, the theory that is emerging from the detailed simulations of the chaotic dynamics of collapse, bounce, delay to explosion, and explosion is beginning to be predictive of the systematics with progenitor properties of explosion energy, neutron star birth mass, nucleosynthesis, pulsar spins and kicks, and perhaps even birth magnetic fields [2, 3].

We will not, however, summarize in this brief offering the rich and complicated subject that is core-collapse supernova (CCSN) theory and its emerging explanatory power. Though these are heady times in the theory of one of the centermost problems in theoretical astrophysics, a vast and developing literature must substitute for such an ambitious endeavor. Rather, we here provide a storyboard in graphical form depicting some of the salient new aspects of CCSN explosions and neutron-star birth that we feel compelled to highlight, as revealed by our recent 3D simulation efforts [4–8]. Reviews of basic supernova physics can be found in [9–11]. Important 3D simulation work by other research groups (by no means exhaustive) can be found at [12–18].

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2 Collapse, Bounce, Stall: A Turbulent Outer Convective Region Bounded by a Shock Wave

Figure 1 depicts a representative snapshot ∼150 milliseconds after core bounce of the stalled shock wave (blue veil) bounding the neutrino-heating-driven convective shell that surrounds the inner proto-neutron star (PNS) (yellow ball) just prior to explosion. The tangle of trajectories in this turbulent region just interior to the stalled shock traces representative matter motions. The initial model is not rotating, so the collapsing matter comes in radially and this material is depicted on the outside of the plot with representative radial tracers. The hydrodynamic stress in the turbulent region interior to the shock, along with the neutrino energy deposition behind the shock, are together responsible for launching the explosion after a delay (depending upon the progenitor structure and mass) of generally 100−500 milliseconds. This figure summarizes the major regions in the engine of core-collapse supernova explosion. Note that the snapshot extends only ∼300 kilometers (km) on a side, but resides in a star that might have a radius comparable to the radius of Jupiter's orbit. Hence, this small, dense, and hot core region is the highly energetic "mote in the eye of the storm." The explosion is launched into the rest of the star within seconds of bounce, but it is destined to take hours to a day to reach the progenitor star's periphery.

3 The Asymmetric Explosion Morphology: Bubbles and Fingers

Figure 2 depicts two different orientations of the same explosion structure after the ignition of the blast of an initially non-rotating 25-$M_\odot$ progenitor star near 550 ms after bounce. The pale blue veil is the shock wave and the surfaces are isoentropy surfaces colored by electron fraction (Y_e). The latter will translate roughly into element composition asymmetries. Clearly shown are the bubble-like elements that characterize explosions by the neutrino heating process that also generically drives convection. For models such as this 25-$M_\odot$, there is frequently a front-back dipolar structure and many finger structures. This is particularly in evidence for the more massive progenitors which might explode after a greater delay, allowing for more violent and vigorous turbulence. Also a feature of this figure and model, though not as obvious, is the fact that matter is still accreting in a ring structure, pinching to achieve a "wasp-waist" shape. Simultaneously accreting in one direction, while exploding in another, allows the maintenance at respectable levels of the accretion-powered component of the driving neutrino luminosity. This breaking of symmetry, not possible in 1D (spherical) explosions (if they do or could occur), is an important feature of the multi-dimensional CCSN explosion mechanism.

Figure 3 is a similar rendering of the explosion of a 9-$M_\odot$ model, with and without moderate rotation (initial core Ω_0 = 0.1 rad s^{-1}) [19]. From the vantage of blast structure, only very rapid rotation is likely to have a noticeable effect. Figures 2 and 3 serve to indicate that all our models explode aspherically and that CCSN explosion debris distributions are inherently complicated. Figure 4 is the same 25-$M_\odot$ model portrayed in Figure 2, but at a later time and with representative debris matter trajectories. On the left side of the figure, the small bulbous structure is defined on its inner side by the pinching due to some residual accretion (via the "wasp waist").

4 The Birth of a Neutron Star and Inner Proto-neutron-star Convection

Most core-collapse supernova explosions leave behind a proto-neutron star residue. This object is hot and lepton-rich, but through neutrino losses over many seconds to a minute contracts, deleptonizes, and cools to leave a compact neutron star with a radius of ~12 km. Such an object might eventually be observed as either a radio pulsar or a magnetar. Figure 5 depicts the PNS and its surroundings created in the explosion of the 25-$M_\odot$ depicted earlier. The scale is about 300 km on a side. The outer tangle traces with representative mass trajectories the convective region just interior to the supernova blast wave (off the scene and not shown). The roughly spherical surface is an isodensity surface at $10^{9.5}$ g cm^{-3} painted by Y_e, interior to which is revealed after grahpical slicing the continuation of the outer convective tangle. Interior to that is a quiescent radiative zone and further in is a convective inner core. The latter might be the sight of magnetic dynamo action [3]. This PNS structure is a star in and of itself, whith convective and radiative zones, that our Fornax code follows in 3D.

The same object a few hundred milliseconds later is portrayed at the same scale in Figure 6. We see that because of ongoing neutrino losses the PNS has shrunk and outer convection is beginning to subside. As noted, this process will continue for some time into the future, eventually leaving a cold, catalyzed, compact neutron star. One can estimate that currently there are $\sim 10^8$ such neutron stars in our galaxy.

5 The Possibility of Induced Pulsar Spin

Even for initially non-rotating models, the PNS core left behind can be left rotating. At late times after explosion, matter is still infalling. Due to the turbulence, such matter is not falling in spherically, but with non-zero impact parameters. Each accreted matter blob will impart angular momentum with a range of magnitudes and directions and it is the vector sum of these accretions that will determine the integrated resultant angular momentum given to the newly-born neutron star. The opposite signed vector angular momentum will be imparted to the ejected. Hence, through stochastic processes of random accretion, the PNS can obtain a spin when its initial spin, and that of the progenitor star, was zero [20, 21]. Figure 7 depicts the core near the end of our 25-$M_\odot$ simulation. The tracers enveloping it indicate clearly that many are spinning roughly coherently and that the outer PNS has a net spin. In fact, these and other CCSN calculations indicate that, given the stochastically accreted angular momentum of the core, the final period of the entire residual mass due to this induced process can be $\sim 500 - 1000$ ms. Though not very fast in the overall context of pulsars, this range is quite interesting, suggesting that induced rotation may have a role in a subset of core collapses.

6 Conclusion

In this short paper we have tried merely to indicate the complex character of the hydrodynamics that attends the dynamical evolution of the cores of massive stars in their terminal phases that are the energetic seat of core-collapse supernova explosions and neutron star birth. We have not attempted to provide detailed explanations of the radiation/hydrodynamics, the neutrino-matter couplings, nor the physics that underpins the phenomenon. It is merley our hope that the reader gleans through this graphical montage some sense of the flavor of the modern emerging theory of this central astrophysical problem.

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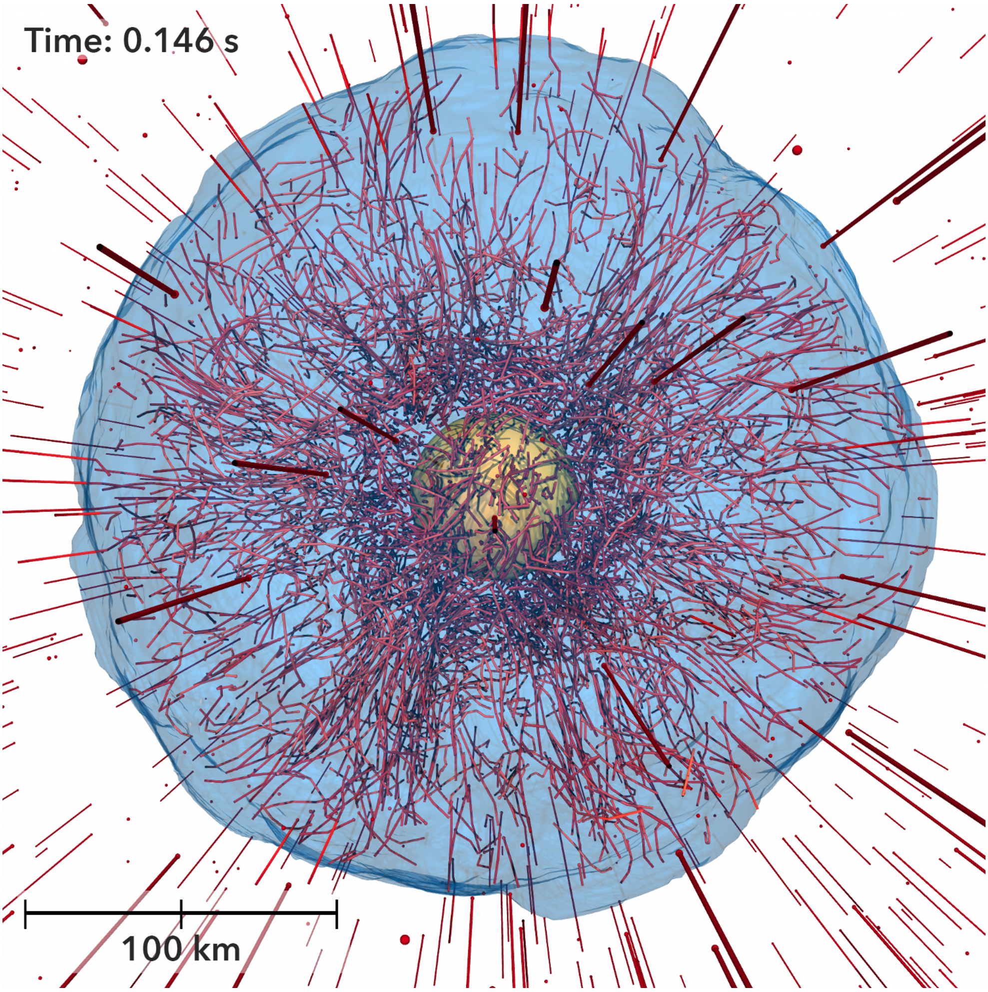

Figure 1. Ther inner structure of the proto-neutron star, bounded by the accretion shock wave (blue) just prior to explosion. The neutrino-driven turbulent region is just interior to the stalled shock is traced by the tangle of snapshot trajectories. See the text for more detail.

https://doi.org/10.1051/epjconf/202226007001

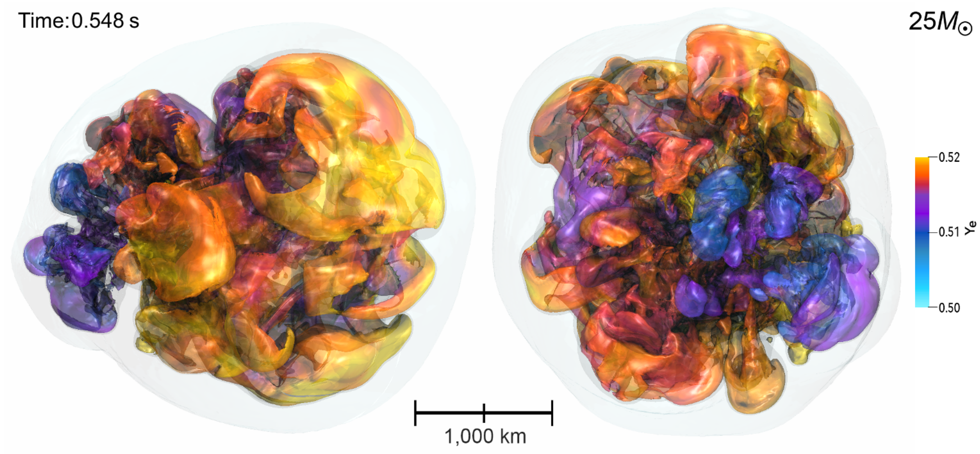

Figure 2. Two vantages of the exploding debris just 0.548 seconds after core bounce. The blue veil is the shock wave and the surfaces are isoentropy surfaces, colored by Y_e. The scale is ~3000 km. See the text for a discussion of this figure.

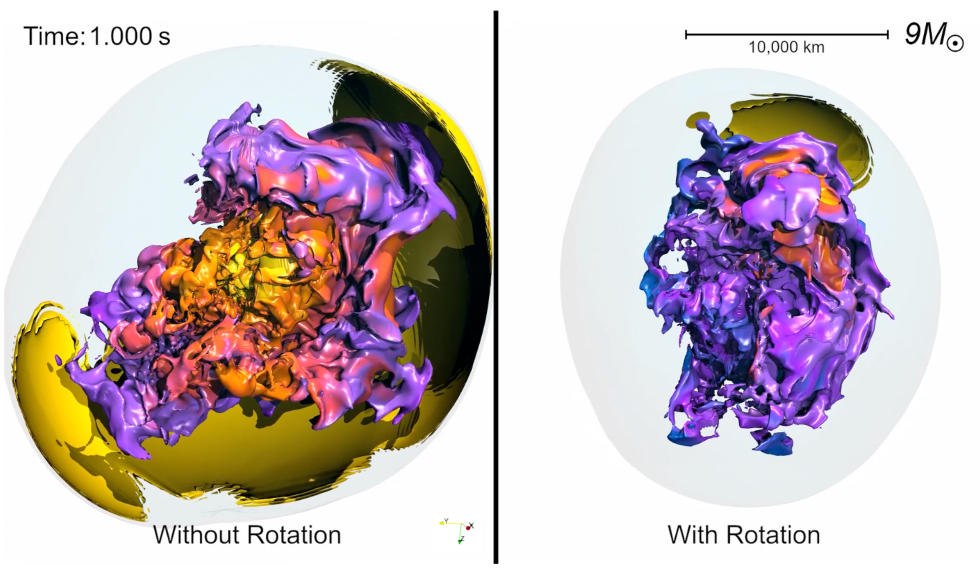

Figure 3. Similar to Figure 2, but comparing a modestly rotating model of a 9-$M_\odot$ explosion with the corresponding non-rotating model. See the text for more information.

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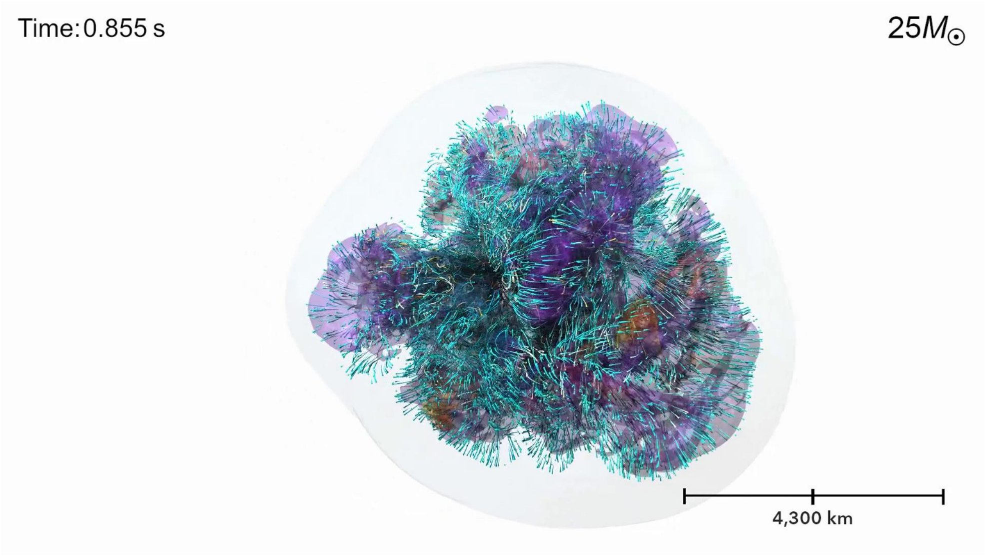

Figure 4. The blast wave with a traced debris cloud of the core of a 25-$M_\odot$ progenitor just one second into its explosion. The scale is near 10,000 km. See the text for a discussion.

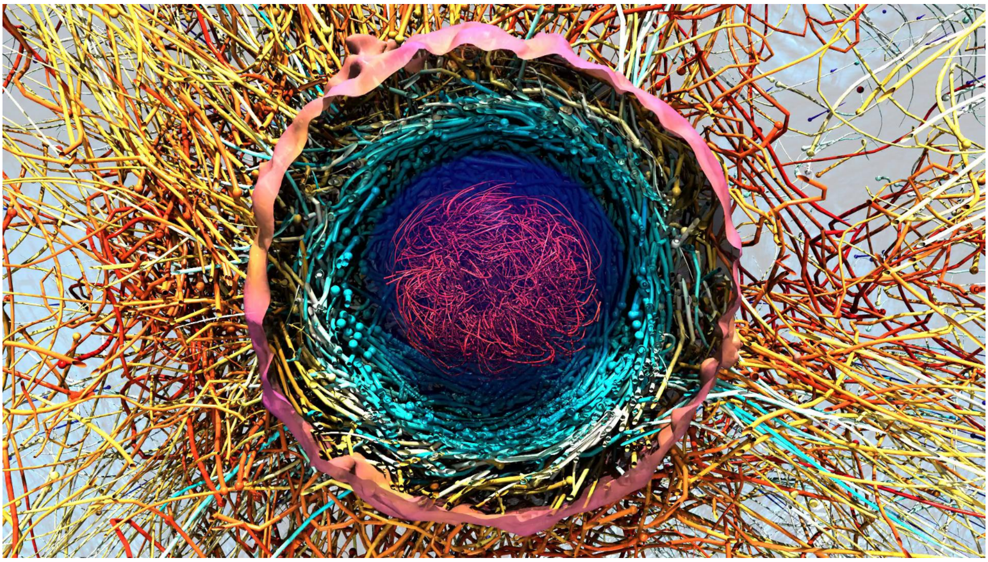

Figure 5. A snapshot from a simulation conducted by the Princeton supernova group [8] on Theta/ALCF of the supernova explosion a 25-$M_\odot$ star, depicting here the early evolution of the neutron star left behind. The scale is roughly 150 kilometers on a side and the time is roughly 500 milliseconds after core bounce and roughly 100 milliseconds after the inauguration of the explosion. The ragged pink shell is an isodensity surface at $10^{9.5}$ grams per cubic centimeter. The tangle in its exterior is of a representative collection of mass tracer particles in the outer convective zone interior to the blast wave (not shown, but beyond a thousand kilometers off the scene), and the inner “ball of yarn" traces the convective motions of the residual proto-neutron star. Convection in this inner region may be the site of a magnetic dynamo that generates magnetar and/or pulsar magnetic fields. Within one minute this core will have shrunk to a radius near 12 kilometers and cooled off to become one of the neutron stars that litter the galaxy. The colors depict the different electron fractions (Y_e) of the matter determined by the dynamical competition of electron-neutrino capture and electron capture on nucleons.

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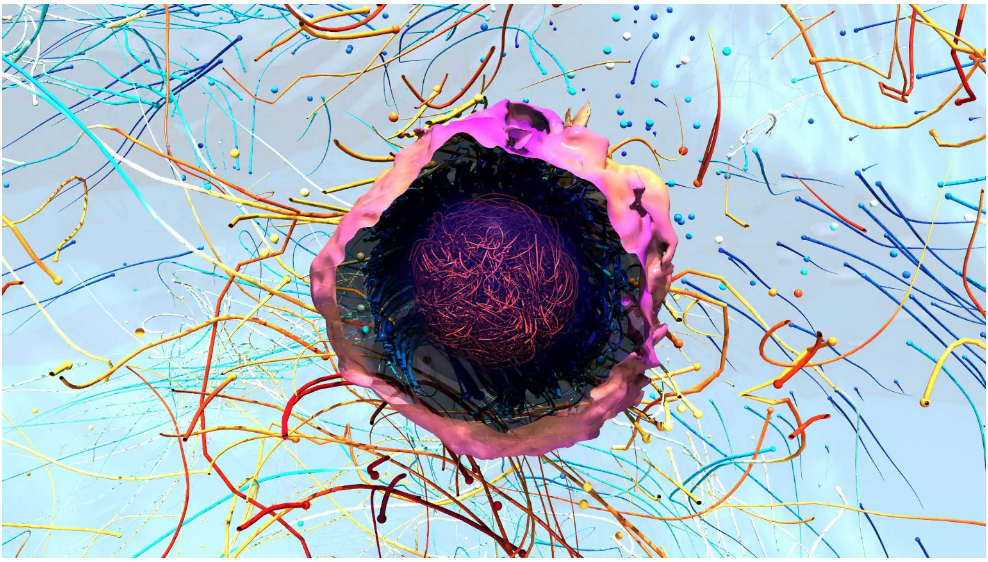

Figure 6. The same as Figure 5, but at a later time. See the text for a description and explanation.

Figure 7. An even later snapshot of the residual core, showing the degree to which the core has further shrunk and the rotating matter that now swirls at the periphery of the PNS. See the text for the context and an explanation.