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Understanding Convection in the Core-Collapse Supernovae Engine[1]

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Abstract—Understanding the nature of the standard engine behind core-collapse supernovae (SNe) has been an active area of research for over 60 yr pushing the limits of computational science. Driven by observations, scientists have developed and refined a model that not only explains existing observations but made predictions that have since been validated by subsequent data. Turbulent-driven convection plays a key role in this explosive engine and producing quantitatively accurate supernova models requires understanding this convection. Here, we review the convective-engine and discuss improved methods to study this convection to solve the supernova problem.

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1. UNDERSTANDING THE SUPERNOVA ENGINE: A TAIL OF TWO SUPERNOVAE

An explosion powered by the potential energy released when the stellar core of a massive star implodes in on itself to form a neutron star seems a fantastical explanation for astrophysical transients known as supernovae. But this is exactly what theorists correctly predicted in 1938 [1]. Although this energy source for core-collapse supernovae has been known for over 80 yr, understanding how to extract that energy has taken much longer. Indeed, the current paradigm by which potential energy is converted to explosion energy was not realized until over 50 yr later. We are still working to understand the details of this engine today.

The details of this engine evolved from a combination of increasingly sophisticated numerical simulations coupled with a wide set of observations that helped place constraints on these simulations. We can distill this more than 80 yr odyssey through the stories of two particular supernova observations: SN 1987A and the Cassiopeia Supernova remnant. SN 1987A validated many of the ideas behind the core-collapse engine. The observation of its progenitor star, Sanduleak-69 202 [2], prior to the explosion and its absence after the explosion, strongly supported the idea that this supernova formed in the death of a massive star. The neutrino observations from this event matched the signal predicted form the collapse of the core of Sanduleak-69 202 down to a neutron star [3, 4]. For this supernova, the observed properties supported the core-collapse engine.

However, SN 1987A also demonstrated deficiencies in our understanding of the supernova explosion model. The progenitor was a blue (compact) supergiant, not the red (extended) supergiant expected from stellar evolution models for a 15–20$M_\odot$ star at collapse. To this day, we are still comparing and testing stellar evolution models against the progenitor of this nearby supernova explosion [5]. The detailed properties of the SN 1987A explosion were also different than what we expected. For example, it is known that the ^{56}Ni is produced in the innermost ejecta of the supernova where the temperatures are sufficiently high to rapidly burn the silicon in the core. This material is produced in the innermost ejected material that, according to 1D simulations, should be the slowest moving ejecta. We can measure this velocity by either observing the gamma-rays produced from the decay of the ^{56}Ni or observing the Doppler broadening of its decay products (i.e., iron). What we observed was very different from the expected slow-moving ejecta. In the case of the gamma-ray observations, we expected a delay in the gamma-ray emission because, initially, the density would be so high that gamma-rays would be down-scattered in the expanding ejecta. Only after the ejecta expanded and became more rarefied would we observe these gamma-rays. In contrast, the gamma-rays emerged far earlier than simulations predicted at the time [6]. If formed in the core, somehow this ^{56}Ni must have been mixed into outer layers of the

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star. Other evidence, including the Doppler broadening of the iron produced from this decay, demonstrated a much faster expansion velocity than expected. All of this evidence suggested extensive mixing and large-scale asymmetries in the SN 1987A explosions [7].

Scientists studied a range of ways to produce these asymmetries [7], but ultimately studies focused on asymmetries in the explosive engine itself [8, 9]. In explaining SN 1987A, the convection core-collapse engine was born. This engine built upon the understanding from past work on the collapse of the core. The basic picture begins with the understanding of stellar evolution. Massive stars undergo a series of successive burning stages until they build an iron core in its center. The iron cores of these massive stars continue to grow with silicon shell burning until the thermal and electron-degeneracy pressure is no longer sufficient to support them. As the cores compress, the conditions in the core become sufficiently extreme to (a) cause the iron to dissociate into alpha particles (removing thermal energy) and (b) the electrons to capture onto protons, producing a neutron and an electron neutrino (removing electron degeneracy pressure). This leads to further compression that accelerates the dissociation and capture, leading to a runaway collapse of the core. The core collapses until it reaches nuclear densities, where nuclear forces and neutron degeneracy pressure cause the core to bounce, driving a shock outward that stalls when energy losses from neutrino emission saps the shock's strength.

The extensive mixing in SN 1987A led astronomers to believe that the engine itself must be asymmetric and they realized that low-mode convection could produce these asymmetries [8, 9]. This convection also provides the means to convert the potential energy released in the collapse into explosion energy. Scientists found that the region between the proto-neutron star (PNS) and the stalled shock is convectively unstable and these instabilities could quickly grow to strong convection. The growth time of this convection is on order of the inverse of the Brunt–Väisäla frequency:

$$T_{\mathrm{growth}} = \sqrt{-\omega_{\mathrm{BV}}^2}, \tag{1}$$

where ω_{BV} is given by:

$$\omega_{\mathrm{BV}}^2 = -g_{\mathrm{eff}}\left(\frac{1}{\rho}\frac{\partial \rho}{\partial r} - \frac{1}{\rho c_s^2}\frac{\partial P}{\partial r}\right), \tag{2}$$

where c_s is the sound speed, P is the pressure, and $g_{\mathrm{eff}} = -\partial\Phi/\partial r + v_r \partial v_r/\partial r$ is the effective gravity with Φ is the gravitational potential and v_r is the radial velocity. For the region above the proto-neutron star, the growth time can be approximated by:

$$T_{\mathrm{growth}} \approx \sqrt{-\frac{GM_{\mathrm{PNS}}}{r_{\mathrm{PNS}}^2}\frac{\Delta S}{S\Delta r}}, \tag{3}$$

where G is the gravitational constant, M_{PNS}, r_{PNS} are mass and radius of the newly-formed, proto-neutron star, S is the entropy and ΔS is the change in entropy of a distance Δr in the region between the proto-neutron star and the stalled shock. With these conditions, we find the post-bounce convective growth-time to be on order of a few milliseconds [10].

Although we can analytically estimate the growth of convection, simulating the convection and its growth has been more challenging. Because of the broad physics needed in core-collapse calculations, the convective instabilities were grossly under-resolved, leading to slower growth times even in the linear regime. But when convection did occur, it dramatically altered the fate of the explosion. Figure 1 shows a 2D slice of a 3D model of the convection region. This slice shows the collapsed core after the development of convective instabilities. High-entropy material heated by the neutrinos emitted at the surface of the proto-neutron star surface rise in bubbles and low-entropy material supplied from the still-infalling star streams down the stalled shock [11]. This convection facilitates the explosion by doing two things: (a) prevent the pile-up of material because the infalling material is allowed to stream through top of the stalled shock, reducing the pressure the engine must overcome to drive an explosion with respect to a 1-dimensional model and (b) allow material heated near the proto-neutron star surface to rise, converting its thermal energy into kinetic energy to drive the explosion. Both of these affects (and perhaps more) contribute to enhancing the explosion potential of stellar collapse.

This convective engine also explained one of the longest-standing issues in our understanding of the supernovae: why do most supernovae explode with the energy of ~10^{51} erg when the potential energy released is 10^{53} erg? The pressure of the infalling star is such that roughly 10^{51} erg is needed to overcome this pressure and drive an explosion. Once the explosion is launched, it becomes increasingly difficult to deposit additional energy into the explosion because the outflow ultimately halts the infall of material and the material becomes too diffuse to absorb much neutrino energy. The low-mode convection expected in this engine [12] would produce asymmetric explosions that could drive the enhanced mixing seen in SN 1987A. Finally, this model predicted that only lower-mass stars (roughly less than $20 M_{\odot}$) could produce supernovae [13]. This prediction was ultimately borne out when a large enough sample of supernova progenitors was observed [14].

With the discovery of gamma-ray bursts and the collapsar model [15], scientists started to invoke these alternative engines (accretion disk and magnetar driven) for normal supernovae, despite the fact that they were initially proposed solely for super-energetic explosions, not to explain normal supernovae. Indeed,

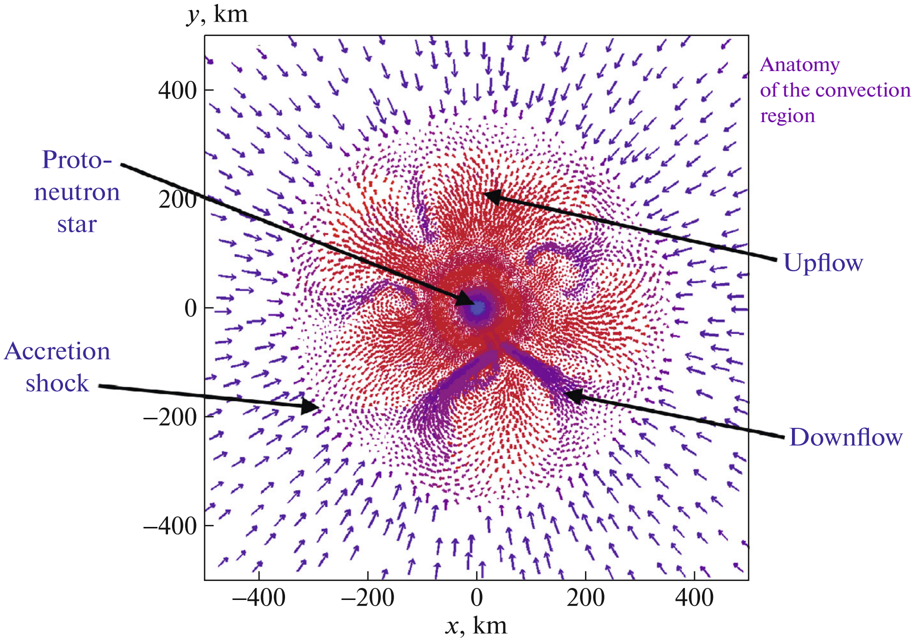

Fig. 1. 2D slice of a 3D simulation of the core-collapse supernova engine. The arrow magnitude and direction dictate the magnitude direction of the velocity. The color dictates the entropy. The proto-neutron star, accretion shock of the imploding star, upflows and downflows of the convection are labeled.

these alternate mechanisms can neither explain the fact that normal supernovae are $\sim 10^{51}$ erg nor the fact that supernovae occur in stars with progenitors less massive than $20 M_\odot$. Although these observations rule out disk models as standard supernova engines, the excitement over gamma-ray bursts led scientists to invoke magnetar or accretion disk jets for a wide range of events. One such object was the Cassiopeia A supernova remnant. The shock-heated silicon features[2] exhibit a jet-like structure [16]. To determine whether this feature is caused by a jet-driven explosion or asymmetries in the circumstellar medium, scientists needed to observe the innermost, as yet unshocked, ejecta. The NuSTAR satellite [17] was designed to observe the decay of radioactive ^{44}Ti, a tracer of the innermost ejecta (along with ^{56}Ni). The nature of the explosion (jet or convective) would still be imprinted in this ejecta material. NuSTAR observations matched the predictions of the convective engine (and not the jet-like features predicted by the magnetar engine), providing direct support to the convective-engine paradigm developed by theory through the course of a series of increasingly complex models. Once again, observations have validated the convective-engine model.

Despite the success in explaining observations, more quantitative results (e.g., exact explosion energies, etc.) have remained elusive. The nature of the supernova explosion is that its success sits on a cliff. Some models explode, form strong supernovae and neutron star compact remnants. Others fail to explode, producing a black hole and either no explosion or, if the star is rapidly rotating, a gamma-ray burst. To achieve quantitative results, we must understand this convection in detail.

2. UNDERSTANDING CONVECTION

Although a broad range of physics remains important in the core-collapse engine: behavior of dense nuclear matter, neutrino interactions, neutrino oscillations, nuclear burning, magnetic fields, etc., the problem gets much more difficult in the convective-engine paradigm. To complete the first-principles, full physics model of the convective engine, this convection must be resolved in 3D, a task that is well beyond the current or future capabilities of even the most powerful supercomputers. To solve this problem, scientists will have to understand this convection and implement subgrid models to capture this physics.

Analytic approximations can be used to help us better understand this convection. Astrophysicists have long used mixing-length theory to understand convection in stars. In this paper, we will use this formalism to study the growth of convection in the collapsed core out to the stalled shock. The mixing-length theory

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[2] As the supernova blasts through the circumstellar medium, it slows down, producing a reverse shock that runs back through the supernova ejecta, reheating it. This heating leads causes the remnant to light up and this is what we observe.

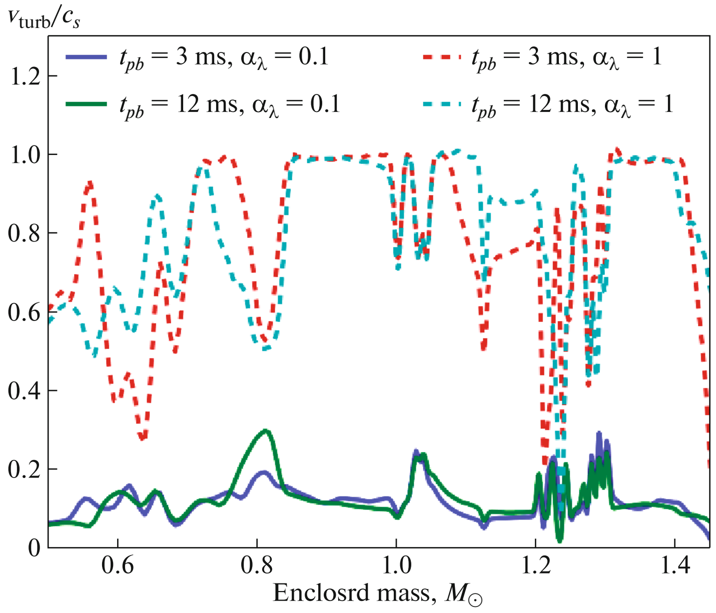

Fig. 2. Turbulent velocity divided by sound speed applying our mixing length prescription to the post-bounce structure of a collapsed core for two different mixing length scale heights: $\alpha_\lambda = 0.1, 1$. We also allow this convection to grow for 3 and 12 ms. Convection occurs both above and below the proto-neutron star surface (roughly at $0.8M_\odot$).

solution we apply is identical to the one described in detail by [18]. If we focus on the source terms (neglect the flux terms), the turbulent velocity growth is described by:

$$\frac{\partial(\rho v_{\rm turb}^2)}{\partial t} + \text{Flux Terms} = \rho v_{\rm turb}\omega_{\rm BV}^2\Lambda_{\rm mix} - \rho v_{\rm turb}^3/\Lambda_{\rm mix}, \qquad (4)$$

where ρ is the density and $v_{\rm turb}$ is the turbulent velocity. Here we again use the Brunt-Väisäla frequency ($\omega_{\rm BV}$). $\Lambda_{\rm mix}$ is the mixing length set to a fraction α_Λ of the pressure scale height. Fig. 2 shows the turbulent velocity divided by the sound speed applying our mixing-length profile in a fixed post-bounce structure. The post-bounce structure is for a $15M_\odot$ progenitor modeled in 1D from the onset of collapse through bounce (for more details, see Fryer et al., 2021, in preparation). In this figure, the convective velocity is allowed to grow (without changing the structure) for 3 and 12 ms. We also vary the mixing length from 10–100% of the pressure scale height. The growth time does not affect the turbulent velocity, but the mixing length does.

In this post-process calculation, we see that the convection grows quickly (within a few ms) and can be extremely powerful (reaching the sound speed) depending on the exact details of the convection. Such turbulent velocities point to additional compressible flow phenomena, such as acoustic wave interactions, shocklet heating, and pressure-dilatation energy transfer, further enhancing the mixing. In this preliminary study, we only varied the mixing length. But a thorough study requires exploration of different drivers behind the convection to determine its growth. Mixing length theory was developed for astrophysics in the 1950s [19] prior to the full realization of the Kolmogorov cascade description and inertial range scaling laws [20]. If mixing-length theory implementation in astrophysics codes had come after, it might have incorporated this more complete understanding of turbulence [21]. Reynolds Averaged Navier–Stokes solutions have long been used in the turbulence and engineering communities to develop more accurate methods [22]. We plan a much more detailed study of these models in a future paper.

3. OBSERVATIONAL IMPLICATIONS

The broad implications of the core-collapse supernova engine makes solving this convective engine particularly important to a wide range of astrophysics fields. Here we list just a few of them:

- **Determining which stars produce explosions:** The growth time of the convection is important because of the transient nature of the supernova engine. After the bounce, the outer layers of the star continue to implode, building a layer on top of the stalled shock. As we discussed, convection enhances the explosion and, with quantitative models, we can determine which stars explode and which do not. In turn, this also determines which stars can form transients like gamma-ray bursts assuming the collapsar model is key in making long-duration gamma-ray bursts.

- **Compact remnant mass distribution and the mass gap:** The faster the convection grows, the quicker the explosion. If the convection drives an explosion quickly, it is likely to be more energetic producing a strong explosion that drives off the entire star leaving behind a neutron star with a mass close to that of the proto-neutron star [23]. In this scenario, core-collapse produces a bimodal distribution of compact remnant masses separated by a mass gap. If, instead, the explosive engine takes longer to develop, the explosion will be weaker, allowing some material that is initially flowing outward to fall back under gravity. This produces a much broader compact remnant mass distribution.
- **Gravitational wave and neutrino signatures:** The nature of the convection will also alter the gravitational wave and neutrino signals. These can be used as an alternative probe of the convection's nature.

Turbulent convection is difficult to resolve with the detailed physics needed to understand supernovae. Much more work remains in order to produce accurate results from these explosions. But understanding convection is key and will dominate our studies in the near future.

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