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Studying Supernovae under the Current Paradigm

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Abstract. The convection-enhanced paradigm behind core-collapse supernovae (SNe) invokes a multi-physics model where convection above the proto-neutron star is able to convert the energy released in the collapse to produce the violent explosions observed as SNe. Over the past decade, the evidence in support of this engine has grown, including constraints placed by SN neutrinos, energies, progenitors and remnants. Although considerable theoretical work remains to utilize this data, our understanding of normal SNe is advancing. To achieve a deeper level of understanding, we must find ways to compare detailed simulations with the increasing set of observational data. Here we review the current constraints and how we can apply our current understanding to broaden our understanding of these powerful engines.

Keywords. supernovae

1. Evidence For the Current Paradigm

Massive stars evolve until they build a core of iron in their center, supported by thermal and degeneracy pressure. As the mass of this core increases, it compresses until both electron capture onto protons and the dissociation of iron atoms occur. These two processes remove both the degeneracy pressure and thermal pressure supporting the core, causing the core to further compress, ultimately leading to a runaway collapse. The collapse accelerates until the core reaches nuclear densities and nuclear forces and neutron degeneracy pressure halt the collapse, causing the core to bounce. The bounce shock moves out through the star until neutrino losses and, to a lesser extent, iron-atom dissociation sap its energy, causing it to stall. The standard paradigm for core-collapse SNe argues that, after the stall of the shock, an unstable region between the edge of the proto-neutron star and the stall of the bounce shock, is able to revive the explosion. Based on evidence of mixing in supernovae, SN engine theorists proposed that convection above the proto-neutron star enhance the efficiency at which the gravitational potential energy is converted to explosion energy(Herant *et al.* 1994). Within the SN community, this engine has taken nearly 15 years to gain acceptance, but at this time, most arguments focus on the nature of the convection; for a review, see Fryer & Young (2007).

Since the discovery of the neutron, scientists have believed that the implosion of a stellar core to a “star” made of neutrons could be the source of energy for the observed SNe(Zwicky 1938). The neutrinos from SN 1987A argued that at least some SNe are produced in stellar collapse(Bionta *et al.* 1987, Hirata *et al.*1987). Observational support for the convection-enhanced variant of core-collapse comes from a series of observational constraints. First, the explosion energies predicted from the convective engine are limited to roughly the amount of energy that can be contained within the convective region ($\sim$few times 10^{51} erg, Fryer 1999). This provides a natural explanation for the fact that most SN explosions harness only 1% of the 10^{53} erg of energy released in the collapse. But this means that this engine will not work for exotic explosions such as hypernovae.

Matching the explosion energies is a postdiction of the convective engine. An example of a prediction lies in the observations of SN progenitors. The convective engine predicts that it will be more difficult to produce strong explosions from massive stars; arguing that stars more massive than about $\sim 23 M_\odot$ (this depends on the stellar evolution calculations) would not make strong explosions (Fryer 1999). At the time, SN light-curve observations argued that most SNe were produced by stars more massive than $20 M_\odot$ (Hamuy 2001), in direct disagreement with theory. Since this time, observations of SN progenitors have convincingly demonstrated that theory was correct (Smartt 2009) and lower-mass stars dominate the observed supernova progenitors. Another prediction solely made by the convection-enhanced engine is that the inner ejecta should be asymmetric, but not bimodal (Fryer & Young 2007). With the recent NuSTAR observations of Cas A (Greffenstette *et al.* 2014), there is clear evidence of these non-bimodal asymmetries, cementing the importance of this engine as a leading model for normal SN. For a review of all the observational evidence, see Fryer *et al.* (2014).

2. Stronger Ties to Observations

As we home in on the convection-enhanced SN engine for normal SNe, it is important to look for new methods to test this engine. There are two approaches to studying these observations: 1) use existing models, incomplete as they may be, as gold standards and compare their predictions to the observations or 2) use existing models to understand the underlying physical conditions and do a parameter study to compare to observations. The latter is more work, but ultimately has more power to test the model. By parameterizing the SN engine within the constraints of the model (drive power, duration and asymmetry), we can produce theoretical error bars and solutions to study, among other topics, nucleosynthetic yields (Young & Fryer 2007), fallback and compact remnant masses (Fryer *et al.* 2006, Fryer 2009), and SN remnant structures (Hungerford *et al.* 2003, Hungerford *et al.* 2005, Ellinger *et al.* 2012). As we study these solutions, we will gain a better understanding of this standard paradigm and its role in SNe.

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