Core-Collapse Model Effects on Nucleosynthesis

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Abstract

Although simulations of the core-collapse supernova mechanism have not yet converged on a final answer, much of the intuition gained from these simulations can change our current picture of supernova nucleosynthesis. Here we review the basic supernova explosion mechanism with an update on the current status of this mechanism. We then discuss how this picture leads to changes in the current calculations of nucleosynthetic yields from these outbursts. The behavior of the electron fraction, mixing, and explosion energy (as a function of mass) are quite different than the assumptions used in many nucleosynthesis calculations, and we will focus on these issues.

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1 Introduction

The neutrino-driven supernova mechanism was first simulated by Colgate & White (1966). They found that if a fraction of the neutrinos emitted in the collapsed core of a massive star were deposited into the star's envelope, a very energetic explosion could occur. The last 3 decades have led to increasingly sophisticated simulations of stellar collapse with results that oscillate from energetic explosions to weak or no outbursts. Even now, differences in the implementation of neutrino transport have led to a range of supernova results (Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Janka & Müller 1996, Mezacappa et al. 1998; Fryer 1999; Fryer & Warren 2002; Buras et al. 2003).

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Because of the lack of convergence, most nucleosynthesis calculations use simplified assumptions of the explosion physics in their models (e.g. Woosley & Weaver 1995) and, with these simplifications, have achieved fairly good agreement with observations. But despite the differences in collapse simulations, a basic picture for how this mechanism works does exist which can already expose errors in these simplified calculations.

Before we discuss the details of these errors, let's first discuss the basic picture behind core-collapse supernovae. Massive stars go through a series of burning stages: hydrogen to helium, helium to carbon and oxygen... through a series of nuclear burning phases with heavier elements which finally ends with an iron core that grows as the Silicon layer above it produces more and more iron. This iron core is supported by thermal and electron degeneracy pressures. Ultimately, the temperature and density in the core reach such high values that the iron dissociates into alpha particles (reducing thermal pressure) and electrons begin to capture onto neutrons (reducing degeneracy pressure). The core collapses.

The collapse continues until the core reaches nuclear densities at which time nuclear forces and neutron degeneracy pressure halt the collapse. The core bounces, sending out a shock wave that was once believed to be the supernova explosion. Most of this bounce shock's energy is in internal energy, and neutrino and dissociation energy losses ultimately cause this shock to stall. However, neutrinos leaking out of the hot proto-neutron star core can deposit energy into the shocked region and revive this shock. The stalled shock leaves behind material that is unstable to convection (negative entropy gradient) and neutrino heating from the proto-neutron star (depositing most of its energy just above the proto-neutron star and the base of the shocked region) drives this convection even further (Fig. 1). Convection converts the energy deposited at the base of the shocked region to kinetic energy which pushes against the infalling material, ultimately driving a supernova explosion (we hope!). This is known as the convection-enhanced, neutrino-driven supernova mechanism.

Woosley & Weaver (1995) produced one of the standard sets of nucleosynthetic yields from core-collapse supernovae. Their 1-dimensional models placed a piston at the edge of the iron core. The piston was first pulled in to simulate collapse and the driven outward to produce a supernova explosion. More massive stars received more energetic explosions and fallback was minimal. Our current knowledge of core-collapse supernovae suggests a much different behavior for supernova explosions. We discuss these differences here.

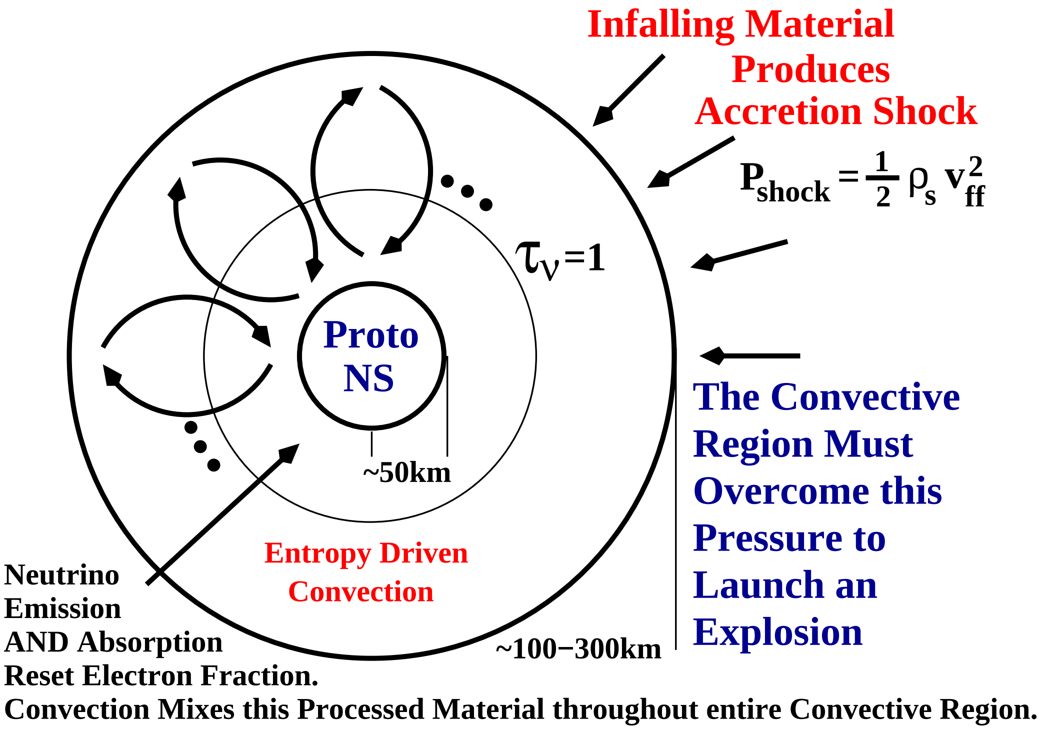

Fig. 1. The neutrino-driven, convection-enhanced supernova mechanism. Neutrinos leaking out of the proto-neutron core (∼50 km in size) heat material above the proto-neutron star. This material rises, converting its thermal energy into kinetic energy which pushes against the infalling star. The boundary between the convective region and the infalling star is marked by an accretion shock. If the convective region can overcome the ram pressure at the accretion shock, an explosion is launched.

2 Electron Fraction and Resetting by Neutrinos

Woosley & Weaver (1995) placed their piston at the edge of the iron core. They did so because the electron fraction in the iron core was so low that it would produce nucleosynthetic yields that do not agree with what is observed in nature. But this assumes that the electron fraction of the exploding material only depends upon the evolution of its progenitor. But as we discussed above, the entire convective region is bathed in the neutrinos leaking out of the proto-neutron star and these neutrinos will change the electron fraction of this material.

If, above the proto-neutron star surface, more electron neutrinos are absorbed than anti-neutrinos, the electron fraction of the absorbing material will rise. For the neutrino luminosities and energies derived from Fryer & Warren (2002), this is the case and even if the progenitor star's iron core had a low electron fraction, the neutrino flux could reset this value. Hence, some of the iron core can be ejected. Indeed, most simulations place the convective region within the iron core (especially for more massive stars) and it is likely that some of the iron core is ejected.

What should be done? One could simply use the neutrino fluxes from the best current supernova models and assume that the electron fraction is set by the relative electron neutrino and anti-neutrino absorption. However, there is not enough neutrino absorption to reset the electron fraction entirely. In addition, much of the material that flows to the surface of the proto-neutron star will also undergo electron capture of its own (Arnett 1968) and this material will be difficult to reset entirely. Probably the best solution here is to include the electron fraction as a free parameter (this has been done before in 1-dimension but needs to be studied in multi-dimensional models) and determine what values can lead to acceptable answers in the nucleosynthesis.

3 Explosion Energy and Fallback

Another assumption made by Woosley & Weaver (1995) is that more massive progenitor stars have more massive explosions. On the one hand, some observations seem to show that more massive stars have more energetic explosions (Nakamura et al. 2001). However, it is likely that these strong explosions, also known as hypernovae, make up only a small fraction of massive stars (§5). For most stars, it is likely that the explosion energy actually decreases with increasing progenitor mass.

Why does the explosion energy decrease with increasing mass? The entropy of the inner $1.2\mathrm{M}_\odot$ of most stellar cores look very similar, from progenitors as low as $12\text{-}15\mathrm{M}_\odot$ all the way up to stars with initial masses of $40\text{-}60\mathrm{M}_\odot$. Hence, the collapse and bounce of all these stars are very similar. Beyond the inner $1.2\mathrm{M}_\odot$ core, these stars begin to look very different. It is this outer core material that provides the ram pressure that prevents the explosion, the so-called "lid" to the pressure cooker. It is much more difficult to overcome this pressure cooker lid for the denser cores of more massive stars.

Fryer (1999) found that for progenitors without mass loss, stars between $\sim$10-$20\mathrm{M}_\odot$ produced strong explosions with neutron star remnants. However, above $\sim 20\mathrm{M}_\odot$, the explosion occured later and its energy was not sufficient to blow off the entire star. Much of the star ultimately falls back and causes the remnant to collapse to a black hole (Fig. 2). These stars do not eject much nickel and their resulting light displays are very weak. Such objects have been observed:

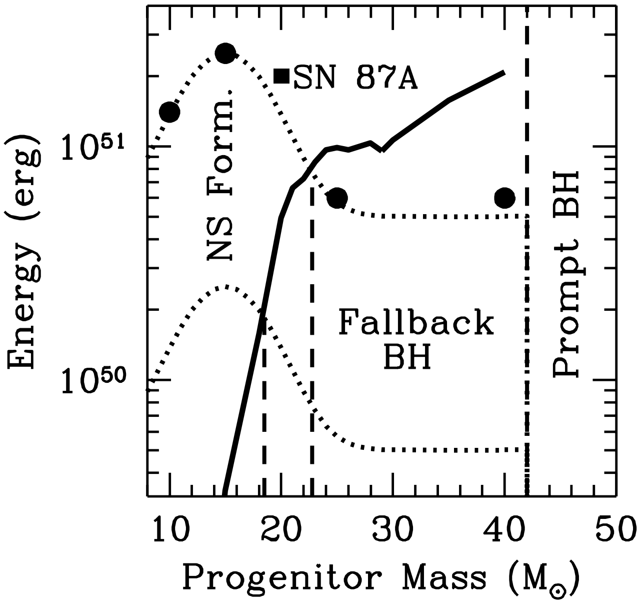

Fig. 2. Fate of massive stars. The solid line denotes the binding energy of the stellar envelope as a function of progenitor mass for stars without mass-loss from winds. By stellar envelope, we mean all the stellar material beyond the inner $3\,M_\odot$. The filled circles denote the explosion energy versus mass from Fryer (1999). The filled square gives the observed explosion energy for SN 1987A. The dotted lines are a fit to the explosion energy. Note that the explosion energy can be lowered by a factor of 10 without changing the transition mass by more than 20-30%.

e.g. SN1997D (Nakamura et al. 2001). Above $\sim 45M_\odot$, stars without mass loss will collapse directly to black holes with no supernova explosion whatsoever (Fig. 2).

What should be done? A more realistic energy profile should be placed into the supernova explosion mechanism. Unfortunately, core-collapse simulations still can not reproduce reliable energies, but Fryer & Kalogera (2001) suggested several energy profiles that, perhaps don't span the range of all possible solutions, but do provide some indication of how the explosion energy might vary. These lower energies may make it harder to reproduce the nucleosynthetic yields in the universe. But remember, we must also account for mixing and hypernovae, and these two effects might account for the differences caused by lower energies: §5,4.

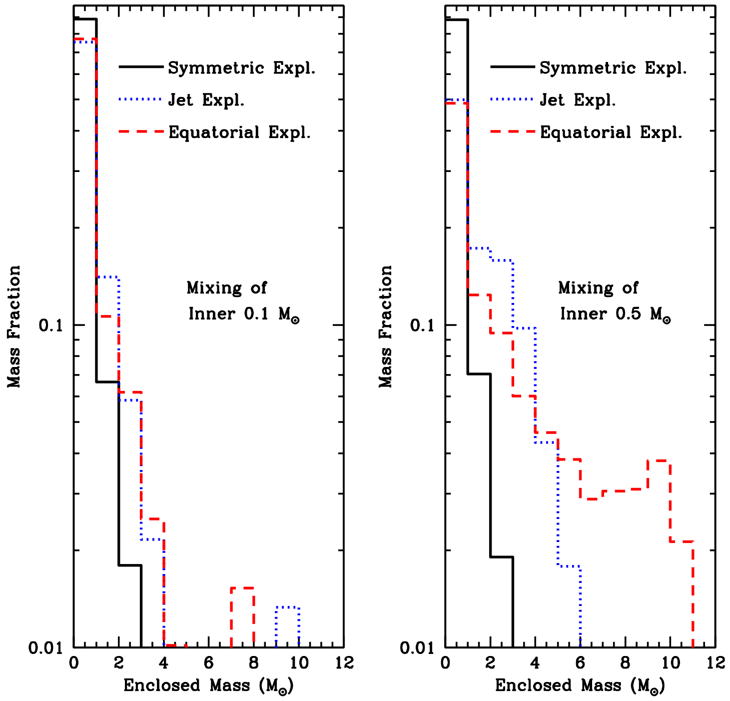

Fig. 3. Amount of mixing of the inner 0.1 $M_\odot$ (left) and the inner 0.5 $M_\odot$ (right) of supernova ejecta for a symmetric explosion with decay energy added in (solid line), a polar explosion with a jet 2 times stronger along the poles than along the equator (dotted lines), and an equatorial explosion with the explosion 4 times stronger in the equator than along the poles (dashed line). See Hungerford et al. (2003) for details.

4 Mixing in Supernovae

The weak explosions Fryer (1999) found for stars $> 20M_\odot$ would not eject the inner $3M_\odot$ of the star's core. It is this inner region where all the explosive nucleosynthesis occurs and, in a 1-dimensional simulation, none of this material would be injected into the universe. But we observe some nickel in the ejecta of weak supernovae such as SN 1997D. This occurs because some of the nickel is mixed out into the outer layers of the star, something the 1-dimensional nucleosynthesis models are only now considering: Woosley & Weaver (1995) do not include this effect, but Thielemann, Nomoto & Hashimoto (1996) do.

Since the early rise of gamma-rays in SN 1987A, it has been believed that mixing must occur in supernovae (see Hungerford, Fryer, & Warren 2003 for a review). Since this time, a number of multi-dimensional studies of the explosion have been performed, but it is just now that it is feasible to study the explosive mixing coupled with nuclear burning of supernovae in its full 3-dimensional glory (Hungerford et al. 2003; Kifonidis et al. 2003). These simulations provide our first real glimpse into the level of mixing that can occur. In a sphericially symmetric explosion of a $15M_\odot$ material in inner $0.5M_\odot$ of the ejecta can mix well into the helium layer (Fig. 3). For asymmetric explosions, the mixing can extend even further (Fig. 3).

What should be done? Thielemann et al. (1996) have sought to parameterize this mixing with a set of mixing parameters. This is the ideal approach. 3-dimensional models spanning a wide range of progenitors and explosion energies can then be used to help set these parameters.

5 Other Explosion Mechanisms

The fact that the neutrino-driven supernova mechanism does not drive strong explosions for stars more massive than $\sim 20M_\odot$ does not preclude strong explosions for these stars. If the progenitor star is rotating, some of the material falling back on the newly formed black hole can "hang up" in a disk. The energy in this disk (either rotational or thermal) can be extracted to drive a strong explosion. This black hole accretion disk mechanism (also known as the "collapsar" mechanism) is believed to produce hypernovae outbursts (Nakamura et al. 2001) and gamma-ray bursts (Woosley 1993).

These objects are rare. Although they are observed nearly 10 times more often than weak supernovae (such as SN 1997D), they produce 50-100 times more nickel and are over 50 times more luminous. In a luminosity limited sample, the observational volume of hypernovae is more than 300 times larger than that of weak supernovae. With such small number statistics it is impossible to truly derive rates. Even if all stars rotate at the right speed to form a black hole accretion disk,it is likely that less than 10% of all stars more massive than $20M_\odot$. Given that stars more massive than $20M_\odot$ make up less than 25% of all stellar collapses, hypernovae make up less than a few percent of all core-collapse explosions. Because not all stars have sufficient rotation to make black hole accretion disks, this fraction is an upper limit.

But even though the rate of these energetic explosions is small, they do produce nearly 10 times the amount of nickel found in normal supernovae and, ultimately, their yields can not be neglected.

What should be done? The yields of these highly asymmetric explosions must be modeled and included in any nucleosynthesis model of the universe.

All of the above effects will make a difference in the nuclear yields from stellar collapse. Modern nucleosynthesis models must include these effects.

References

Arnett, W. D. 1968, *ApJ*, **153**, 341

Buras, R., Rampp, M., Janka, H.-Th., & Kifonidis, K. 2003, *submitted to PRL*

Burrows, A., Hayes, J., & Fryxell, B. A. 1995, *ApJ*, **450**, 830

Fryer, C. L. 1999, *ApJ*, **522**, 413

Fryer, C. L., & Kalogera, V. 2001 *ApJ*, **554**, 548

Fryer, C. L. & Warren, M. S. 2002, *ApJ*, **574**, L65

Herant, M., Benz, W., Hix, W.R., Fryer, C.L. & Colgate, S.A. 1994, *ApJ*, **435**, 339

Hungerford, A. L., Fryer, C. L., & Warren, M. S. 2003, accepted by ApJ

Janka, H.-Th., & Müller, E. 1996, *A&A*, **306**, 167

Kifonidis, K., Plewa, T., Janka, H.-Th., & Müller, E. 2003, accepted by A&A

Mezzacappa, A., Calder, A. C., Bruenn, S. W., Blondin, J. M., Guidry, M. W., Strayer, M. R., & Umar, A. S. 1998, *ApJ*, **493**, 848

Nakamura, T., Umeda, H., Iwamoto, K., Nomoto, K., Hashimoto, M., Hix, W. R., & Thielemann, F.-K. 2001, *ApJ*, **555**, 880

Thielemann, F.K., Nomoto, K. and Hashimoto, M. (1996), *Ap.J.*, **460**, 408

Woosley, S.E. 1993, ApJ, 405, 273

Woosley, S.E. and Weaver, T.A. *Ap.J.Suppl.*, 1995, **101**, 181.