Multidimensional CCSN Simulations with FLASH

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FLASH as a tool for studying CCSNe

EOS effects in simulations with parametric neutrino heating in 1D and 2D

Beyond 2D

Magnetorotational CCSN
FLASH Capabilities Span a Broad Range...

- Cellular detonation
- Helium burning on neutron stars
- Richtmyer-Meshkov instability
- Wave breaking on white dwarfs
- Nova outbursts on white dwarfs
- Laser-driven shock instabilities
- Rayleigh-Taylor instability
- Gravitationally confined detonation
- Orzag/Tang MHD vortex
- Intracluster interactions
- Orzag/Tang MHD vortex

Shortly: Relativistic accretion onto NS
FLASH Capabilities Span a Broad Range...

The FLASH code

1. Parallel, adaptive-mesh refinement (AMR) code
2. Block structured AMR; a block is the unit of computation
   - Originally designed for compressible reactive flows
   - Can solve a broad range of (astro)physical problems
   - Portable: runs on many massively-parallel systems
   - Scales and performs well
   - Fully modular and extensible: components can be combined to create many different applications
   - Well defined auditing process
   - Extensive user base
FLASH v4.0

Fryxell et al. (2000) - My FLASH CCSN application shares no lines of code in common with F00.

We are preparing a new ‘FLASH’ paper: Lee, SMC, et al. (in prep). See also A. Dubey et al. (2009).

Open-source. Get it at: flash.uchicago.edu

User contributions accepted!
FLASH v4.0

- Directionally-unsplit staggered mesh MHD solver with constrained transport
- Ideal and non-ideal MHD
- Reconstruction orders: 1 (Godunov), 2 (MUSCL-Hancock), 3 (PPM), 5 (WENO)
- Multiple slope limiters and Riemann solvers (HLL, HLLC, HLLD, Roe, Lax-Friedrichs,...)
- New multipole Poisson solver. Significantly faster, more accurate and efficient.
- Multigroup FLD with HYPRE linear algebra
FLASH v4.0 for CCSNe

- Extension of unsplit solvers to spherical and cylindrical geometries
- Addition of 1.5D and 2.5D rotation
- Finite temperature EOS (via E. O’Connor, stellarcollapse.org)
- Neutrino ‘lightbulb’ heating/cooling
- Deleptonization a la Liebendorfer (2005)
- And new this week: Ray-by-Ray Neutrino Leakage (from GR1D, E. O’Connor)
3D CCSNe Simulations Require Petascale Computing!

- About 70 million zones in 3D (1% angular/radial resolution)
- Argonne Leadership Computing Facility: Intrepid (557 Tera-FLOP BG/P) and next year, Mira (10 Peta-FLOP BG/Q)
FLASH Core – Collapse Application Weak Scaling

- MHD
- UHD
- Ideal

*MHD perfect scaling achieved with bigger AMR blocks*
First Steps: The influence of EOS in parameterized simulations (Couch 2012)

\[ H = 1.544 \times 10^{20} \left( \frac{L_{\nu_e}}{10^{52} \text{ erg s}^{-1}} \right) \left( \frac{T_{\nu_e}}{4 \text{ MeV}} \right)^2 \]
\[ \times \left( \frac{100 \text{ km}}{r} \right)^2 (Y_p + Y_n) e^{-\tau_{\nu_e}} \]

\[ C = 1.399 \times 10^{20} \left( \frac{T}{2 \text{ MeV}} \right)^6 (Y_p + Y_n) e^{-\tau_{\nu_e}} \]

3 EOS in 1D and 2D with s15s7b2: HShen and Lattimer & Swesty (K=180,220 MeV)
L=1.3e52, 600 ms post-bounce:
2D is significantly easier than 1D

LS curves are lower than STOS

LS180 is lower than LS220
2D is significantly easier than 1D

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Ordering with compressibility K?: Not quite.
2D is significantly easier than 1D

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Ordering with compressibility $K$?:
Not quite.
Why do the explosion times depend on EOS?

Difference in alpha-particle abundance causing difference in \((Y_p+Y_n)\)? Tried \((1.-Y_H)^2\) in heating/cooling terms. No qualitative change.

Difference in buoyant convection/turbulence? Look at optical depth through gain region (Murphy, Burrows, & Dolence 2012):

\[ E_k \sim L_{\nu_e} \tau \]
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Could be due to different development of the SASI. The softer LS EOS produce more compact, denser PNS and advective deceleration regions. Thus, acoustic wave generation is more efficient. Denser PNS are better sonic transducers.
Simulations not done, so sorry, no conclusions yet.
What I’d like to do next...

- Magnetic, rotating progenitors!
- How important could MR be for normal supernovae? Aiding neutrinos, shaping explosions, driving explosions?
- How does MR affect the SASI, convection, and turbulence in a range of progenitors?
- What is the threshold in initial P/B above which MR is important?
- Can we better capture the important dynamics of unresolved amplification mechanisms?
Rotation and Magnetic Fields Are Important!

- Important implications for initial spin and B-field of neutron stars
- Possible r-process site (e.g. Winteler et al. 2012)
- Connection to GRBs
- Possible explanation for observational evidence of bipolar SNe (but see, e.g., Hammer et al. 2010)

Figure 1. Winteler et al. 2012
Magnetorotational CCSNe

\[ E_{\text{rot,PNS}} \approx \frac{1}{2} I_{\text{PNS}} \Omega_{\text{PNS}}^2 \]

\[ \approx 9 \times 10^{50} \text{ergs} \left( \frac{M_{\text{PNS}}}{1.5 M_\odot} \right) \left( \frac{\Omega_{\text{PNS}}}{250 \text{ s}^{-1}} \right)^2 \left( \frac{R_{\text{PNS}}}{50 \text{ km}} \right)^2 \]


 Possible importance revisited by Wheeler et al. (2000,2002).

 Recent work by Burrows et al. (2007) and Takiwaki et al. (2009) in 2D, Winteler et al (2012) in 3D.
Magnetorotational SNe

Figure 5 clearly shows the liftoff of the corkscrewing Lagrangian parcels as rotation transitions into spiraling ejection, and then, at larger radii, into a directed jet. In addition, in model M15B11UP2A1H the radius of the shock in the equatorial regions is larger. This is because the equatorial magnetic pressures achieved there at a given time are larger than in model M15B11DP2A1H. This, in turn, is due to the fact that in model M15B11UP2A1H the uniform (''U'') initial poloidal field results in larger accreted fields at later times than in model M15B11DP2A1H, for which the late-time accretion is of matter from the outer core where the initial field decays in the $1/r^3$ dipolar manner. In fact, for model M15B11UP2A1H the equatorial regions join the explosion at later times. This outcome is expected eventually for all models, but due to the different magnetic field structures and magnitudes for the models listed in Table 1, the times to equatorial explosion will vary greatly from model to model.

The particle trajectories implied by Figure 5 and magnetic flux freezing indicate that the ejected material stretches toroidal field into poloidal field, in a reverse of what happens during rotational winding in the inner $10^3$ km. So, in the jet column at large radii the field has a significant poloidal component.

Figure 6 shows radial slices along the poles (solid lines) and along the equator (dashed lines) of both the poloidal (red) and toroidal (black) fields for models M15B11DP2A1H (left panel) and M15B11UP2A1H (right panel) at 635 and 585 ms, respectively, after bounce. Since there is no appreciable rotational shear interior to $10^4$ km, the magnetic fields there have little dynamical effect. It is the fields in the region between $10^3$ and $150^3$ km that are of consequence, since it is here that the magnetic tower is launched and maintained. Figure 6 and $x^{2.3}$ indicate that the fields achieved in this region in these models are comparable to what is expected at saturation for a $P_0$ of 2 s ($10^3$ $15^3$ G). This justifies our focus on these models when assuming $P_0 = 2$ s, despite the fact that we underresolve the MRI.

Figure 7 depicts color maps of the poloidal (left panel) and toroidal (right panel) field distribution for model M15B11UP2A1H, 585 ms after bounce. In both panels, the lines are isopoloidal field lines and the inner 200 km on a side is shown. The relative extents of the red and yellow regions demonstrate the dominance of the toroidal component in the inner zones at these late times well into the explosion, but the presence of a column of yellow/red (high field) along the axis in the poloidal plot attests to the conversion due to stretching by ejected matter of toroidal into poloidal field (see also Fig. 5). Figure 7 also demonstrates the columnar structure of this inner region due to both equatorial accretion (and, hence, pinching) and rotation about the (vertical) axis. However, it should be made clear that the actual field distributions after saturation are likely to be different, and what they are in detail when the MRI is fully enabled remains to be determined.

Figure 8 compares maps of the gas pressures ($P_\text{gas}$; left panels) with the magnetic pressures ($P_\text{mag}$; right panels) for models M15B11DP2A1H (top panels) and M15B11UP2A1H (bottom panels), at various times after their respective explosions.

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Burrows et al. 2007
B-field Amplification in CCSNe


- Field compression: field carried along with collapsing plasma: “flux-freezing”

- Field winding: linear process, wraps up field lines. $B_\phi \approx 2\pi n_\phi B_p$

- Possible (small-scale) dynamo

MRI in the Linear Regime

E.g., Balbus & Hawley (1992), Obergaulinger et al. (2009)

Considering only radial gradients, instability criterion:

\[
C_r = \left[ 1 \frac{\partial P}{\partial r} \left( \frac{1}{\rho} \frac{\partial \rho}{\partial r} - \frac{1}{\Gamma_1 P} \frac{\partial P}{\partial r} \right) + r \frac{\partial \Omega^2}{\partial r} \right] / \Omega^2 < 0
\]

gravity  buoyancy  rotation

\[
k_{\text{FGM}} \approx \left[ -C_r (C_r + 8) \right]^{1/2} \Omega / 4v_A
\]

\[
\omega_{\text{FGM}} \approx (-C_r^2)^{1/2} \Omega / 4
\]

\[
B_f \sim B_0 e^{i\omega_{\text{FGM}} t}
\]

\[
t_{\text{MRI}} \sim \ln \left( B_f / B_0 \right) / i\omega_{\text{FGM}}
\]

\[
B_{\text{sat}} \approx \alpha r \Omega (4\pi \rho)^{1/2}, \alpha < 1
\]
Magnetic, Rotating Progenitors

Heger, Woosley, & Spruit (2005)

- Magnetic torques slow rotation of cores by a factor of 30-50 relative to non-magnetic progenitors
- Standard 15 $M_{\text{Sun}}$ model: 0.2 s$^{-1}$ (v. 8.0 s$^{-1}$)
- 1.5D collapse simulations for 0.2, 1.0, 2.0 s$^{-1}$
Magnetic, Rotating Progenitors
Is (unresolved) MRI turbulence important? Angular momentum transport, viscous heating (e.g. Thompson et al. 2003).

Progenitor structure is still a big uncertainty. Mass loss, binarity, etc.
Conclusions

- FLASH is a great tool for astrophysical simulation, and now CCSNe as well.
- In parametric-neutrino simulations, the time-to-explosion depends on EOS.
- Possibly due to enhanced acoustic flux from PNS accelerating SASI growth.
- FLASH 3D parametric simulations on the way!
- Magnetorotational effects need further study. Could be very important for certain progenitors.
3D Parameterized Models
\[ F_{100}^- = \dot{M} c_s^2 \frac{1 - \mathcal{M}}{\mathcal{M}} \left( \frac{\delta P}{\Gamma_1 P} \right). \]
SN 1987A
Cas A

Hubble, Chandra, Spitzer
Cas A

Hubble, Chandra, Spitzer

Chandra

Fe K
**SN Polarization**

- ALL core-collapse SNe are polarized
- Higher asymmetries in the cores of explosions
- Often show a “dominant axis” in Q/U plane – indicates an elongated explosion
- Loops in Q/U plane indicate non-axisymmetry

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**Figure 5**

(a) Hα and adjacent continuum on the Q/U plane for SN 1987A on June 3, 1987, at the beginning of the fading from peak. The loop structure is now especially prominent. (b) He I λ5876 and adjacent continuum on June 3, 1987. The data at approximately 5600 Å and 6200 Å represent the continuum. The He I line shows a large excursion to Q ∼ 0.7% at 5800 Å at absorption minimum. The data at Q ∼ –1.2% at 6100 Å correspond to the absorption minimum of the adjacent Ba II line. All these features fall closely along the same locus. The dashed line corresponds to the speckle angle (θ ∼ 16°) (Meikle et al. 1987) in the negative quadrant and extrapolated into the positive quadrant as if there were an oblate counterpart to guide the eye. The data have been corrected for the interstellar polarization given by M. Méndez (private communication) and Jeffery (1991b). Figure adapted from Cropper et al. (1988).

Although the photosphere is still in the hydrogen envelope, the hydrogen clearly, in part, reflects the dominant asymmetry of the inner regions. A likely cause for this asymmetry is the nonspherical distribution of the ionization source in the form of a lump of radioactive nickel and cobalt (Chugai 1992). Departures from the dominant axis lead to loops associated with Hα. All the complexities displayed here are topics for more in-depth study.

The next epoch presented by Cropper et al. (1988) is on June 3, 1987, approximately 100 days after the explosion, midway through the decline of the light curve to the radioactive tail and about the time of the jump of the V-band polarization. Figure 5 shows a sample of these data. In the vicinity of Hα, there is again a distinct extension roughly along the speckle angle, but also an interesting loop structure that reflects the nonaxisymmetric interplay of the line opacity with the polarized continuum. The absorption minimum at ∼ 6400 Å corresponds to the data of the most extreme positive Q and U. Significant polarization, primarily along the speckle angle, is shown by Hα up to 1 year after the explosion (Cropper et al. 1988).

The He I λ5876 line and surrounding continuum illustrated in Figure 5b show remarkable uniformity. The data span Q = 0 at U ∼ –1 with an exceedingly well-defined dominant axis with position angle θ ∼ 4°. The displacement to negative U results from the addition of the underlying continuum that adds a wavelength-independent component to the line polarization (Wang et al. 2003b). The polarization angle of this helium feature is not the speckle angle. The simple single-axis behavior of the helium line is in stark contrast with that of the Hα feature. Curiously, the distinct orientation of the He I line is not imprinted in any obvious way on the hydrogen geometry.

As in so many other ways, SN 1987A was also a canonical event in terms of its polarimetry. The data deserve a more thorough quantitative study than has been done, or than we can attempt.
Type IIP Polarization

SN 2004dj

Core revealed

Photospheric Becoming nebular

Visual brightness (mag)

Days since explosion

V-band magnitude

Degree of polarization

Leonard et al. 2006
What Do the Observations Tell Us?

- Massive stars explode all the time, with energies around $10^{51}$ erg!
- They are NOT spherically-symmetric
- They often show general ‘bi-polarity’ with significant non-axisymmetry and time-dependent polarization.
- They leave remnants that often have high kick velocities and strong magnetic fields.
- Some CCSNe are associated with GRBs.
- Mixing & overturn commonly indicated.
In this paper, we have performed 1D, 2D, and 3D numerical simulations of the collapse, bounce, and explosion of a massive-star core. We have found that both the viability and the long-term outcome of the supernova problem depend critically on the dimensionality of the model. In particular, we have observed that the 3D models explode much earlier than their 2D counterparts, even when the 1D models are used as initial conditions. This result leads us to suggest that lack of access to 3D computational resources may have contributed to the non-observation of supernovae in recent 2D simulations.

Critical curves in electron–neutrino driving luminosity ($L_{\nu_e}$) and mass accretion rate ($\dot{M}$) are shown in Figure 6. For a discussion of the meaning and relevance of this figure, see Section 3.6.

The evolution of the average radius of the shock (in kilometers) is given by $\langle R_{\text{shock}} \rangle$. In 3D, this dipolar oscillation exists (Blondin & Mezzacappa 2009), not only for a central aspect of the supernova problem. When the 1D core explodes, we identify this as a point on the critical curve (Figure 6). This result is an undiminished representation of the mean free energy, which in turn determines the free energy needed to overcome a given mass accretion rate at the shock (Murphy & Burrows 2010; Burrows et al. 2006; Ferreres et al. 2010). Rather, the free energy required is 40%–50%, a rather large, yet not always observed in practice.

In 1D, as demonstrated by Murphy & Burrows (2010), the critical curve is given by $L_{\nu_e} = 3.2 \times 10^{52} \text{ erg s}^{-1}$. In 3D, this is reduced in going from 1D to 3D by higher driving luminosities. The upshot is that the magnitude of the neutrino luminosity is in units of $10^{52} \text{ erg s}^{-1}$.

The table below shows the results of our simulations. The critical curves are shown in Figure 6. In 1D, as demonstrated by Murphy & Burrows (2010), the critical curve is given by $L_{\nu_e} = 3.2 \times 10^{52} \text{ erg s}^{-1}$. In 3D, this is reduced in going from 1D to 3D by higher driving luminosities. The upshot is that the magnitude of the neutrino luminosity is in units of $10^{52} \text{ erg s}^{-1}$.

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The neutrino luminosity of supernovae depends on the thermodynamic state of the stellar bubbles, whose surface is cut open by removing a wide cone face. This is illustrated in the upper right image, which shows a simulation of the explosion process.

The upper row of plots compares the neutrino luminosity for different simulations, demonstrating that higher driving luminosities lead to more energetic explosions. The critical curve for electron neutrino driving luminosity is shown in the middle row, indicating the threshold required for a supernova explosion.

The bottom row of images from Hanke et al. (2011) and Nordhaus et al. (2010) provide visualizations of the explosion process in different dimensions, with 1D, 2D, and 3D models shown. The 3D simulation, in particular, captures the complex dynamics of the explosion.

Critical curves in electron–neutrino driving luminosity indicate that there were models that were calculated in 1D, 2D, and 3D. As this table indicates, the corresponding 1D models show that there were models calculated in 1D, 2D, and 3D, and the corresponding 1D models are represented by plus symbols and those of the 15.0 models are represented by asterisks.

The bounce time for the 11.2, 15.0, and 2007 models is shorter at higher dimension than at lower dimension. The critical curve in electron–neutrino driving luminosity is shown in Figure 5, and this figure is discussed in detail in the text.