We use Blue Waters to study:

Variations in massive star explosions

Eric J Lentz
University of Tennessee, Knoxville

S. Bruenn (FAU), W. R. Hix (ORNL/UTK), J. A. Harris (ORNL),
J. Casanova (ORNL), L. Huk (ORNL), C. Keeling-Sandoval (UTK),
R. Landfield (UTK),
O. E. B. Messer (ORNL), E. Endeve (ORNL), A. Mezzacappa (UTK),
J. Blondin (NCSU), P. Marronetti (NSF), C. Mauney (OrSt), K. Yakunin (UTK)

PRAC: (1) Core-collapse Supernovae through Cosmic Time
(2) Impact of Stellar structure on Core-collapse Supernovae and their Ejecta
Why study supernovae?

Why do some stars explode?

What leads up to the collapse?

How does collapse of the core result in an explosion?

Study exotic physics (nuclear matter, neutrinos, GR) and signals (neutrino, GW)

Understand the generation of elements and their ejection.
Reviving stalled shock with neutrino heating

Adapted from Hillebrandt, Janka, & Müller, 2006, Sci. Am 295, 4, 42
# Ingredients

Matching the physical conditions to numerical inputs to reflect the physical fidelity of the system.

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CHIMERA has 3 “heads”

* **Spectral Neutrino Transport** (MGFLD-TRANS, Bruenn) in Ray-by-Ray Approximation using modern neutrino opacities
* **Shock-capturing Hydrodynamics** (VH1 [PPM], Blondin)
* **Nuclear Kinetics** (XNet, Hix & Thielemann)

Multipole gravity w/ Spherical GR correction

Equations of State:

  - Lattimer-Swesty (K = 220 MeV)
  - Cooperstein/BCK: \( \rho < 10^{11} \text{ g/cm}^3 \)

Passive Lagrangian Tracers for post-processing

Bruenn et al. (2018), arXiv:1809.05608
Model History

**Series-A:** Bruenn+2009 (J. Phys. Conf. Ser, 46, 393), Yakunin +2010 (C.Q.Grav, 27, 4005)


**Series-C:** Lentz+2015 (ApJL, 807, L31)

**Series-D:** multiple studies

- 2D solar metal stars (Bruenn+ in prep.)
- 2D zero metal stars (Huk, Hix, Lentz, + in prep.)
- 2D with large (160-species) network (Harris+ in prep.)
- 3D Wedge turbulence study (Casanova+ in prep.)

**Multiple 3D simulations with Yin-Yang grid**

**Series-E:** 2D study of nuclear equation of state (Landfield, 2018, UTK Ph.D., paper: in prep.)

You can guess what series comes next...

- Improved microphysics (SFHo EoS, ...)


**B-series**

12-25 M⊙ Woosley & Heger (2007) progenitors, run 0.8-1.4 sec.

Explosion energies (circles with arrows) fall in range of measured values from observed supernovae.

Arrows indicate 1 sec. additional growth at ending rate. (Stars show D-series equiv.)

C-series

C15-3D  Time = 388.7 ms

Shock organized into large plumes, main plume opposite main inflow. (left)

Lower resolution models (above) delays shock relaunch. (Lentz+ in prep.)


Yellow/green, Red: hot plumes; blue =≈ shock
Heger & Woosley (2010) [D-series (2D zero metal)]

Large Explosion energies correlated to large Proto-NS

Accretion/reheating engine seems more efficient.

Most of these are still running...

Huk, Hix, Lentz, et al., in prep.

Proto-NS (M☉)

D37-HW10: 2.23
D30-HW10: 1.80
D27-HW10: 1.81
D25-HW10: 2.08
D21.5-HW10: 1.69
D20-HW10: 1.62
D18-HW10: 1.52
D15-HW10: 1.46
D11.9-HW10: 1.44
D10.9-HW10: 1.39
D10.6-HW10: 1.36
D10.3-HW10: 1.36
9.6 $M_\odot$: Low-mass w/ low density outside Fe-core (Heger, zero metal)

15 $M_\odot$: (Woosley & Heger 2007, solar)

25 $M_\odot$: (Heger & Woosley 2010, zero metal. Large Fe-core.)
3 Models - 3 Histories

Diagnostic energies -->

15: Grows slowly after shock launch

25: Rapid growth in explosion energy

9.6: Explosion is very quick to start and to saturate

NS Mass growth
Luminosity correlates to PNS mass in few 100 ms after breakout

**D9.6** heating fades quickly (thus low expl. energy)

**D15** heating similar to C15-3D; **D25** heating very strong after breakout
Entropy slice, 20 ms frame interval
Both models form a large outflow (just like C15-3D model) and primary inflow from opposite end.
9.6 M☉, ZERO METAL, 160-NUC. NET

**Right**: Low densities outside Fe-core triggers rapid neutrino-driven explosion with low Ye layer behind shock, creates neutron-rich isotopes (460 ms).

**Below**: Transferred to FLASH hydro to star surface (~1 AU), develops large plumes enveloped in He & embedded in H, 80000 s (22 hr).

Sandoval et al., in prep

Lentz, Hix, Harris et al., in prep
Dense nuclear Equation of State regulates nature of core bounce and neutrino emissions during shock revival.

Newer Equations of State use different numerical methods and are constrained by experimental and theoretical nuclear physics and measurements of neutron stars.

The old "standard" (Lattimer-Swesty-220) is the outlier.

2D models of 15 M☉ WH07 progenitor

Ryan Landfield (UTK Ph.D., 2018)
Blue Waters has...

... generated a lot of simulation data that we are working to analyze. Buried in that data is a lot of interesting behaviors and physics; some of which we've found; some of that I shared today.

... allowed us to examine progenitor variations in structure in 3D and mass variations in 2D.

... allowed us to examine consequences of simulation parameters by examining the important nuclear equation of state and resolution effects in 3D.

... has provided input data for computations of neutrino signals, gravitational wave signals, nucleosynthesis, and disruptions of supernova progenitor stars.

Supernova modeling with Chimera continues to proceed in 2D and 3D with improving microphysics and a widening range of pre-supernova progenitors and in the near future is multidimensional pre-supernova evolution.