Numerical simulations of neutrinos in supernovae : review, recent advances and uncertainties

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Outline

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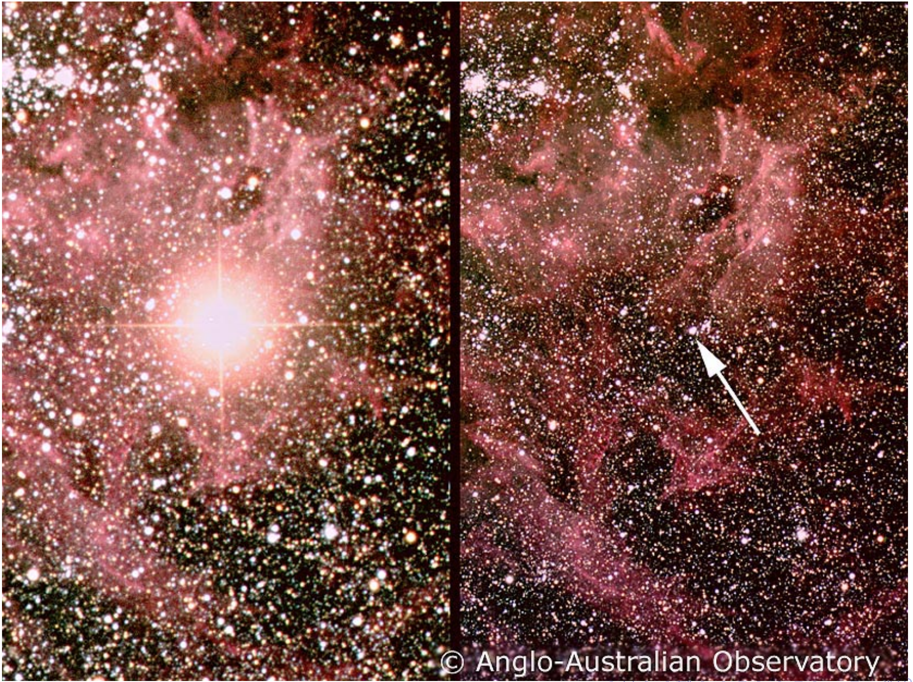
1. Different scenarios for the explosion and the black hole formation
2. Detailed supernovae simulations
3. Neutrino treatment
4. Conclusions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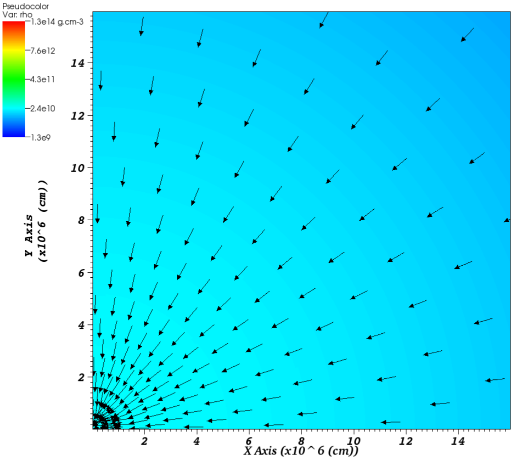
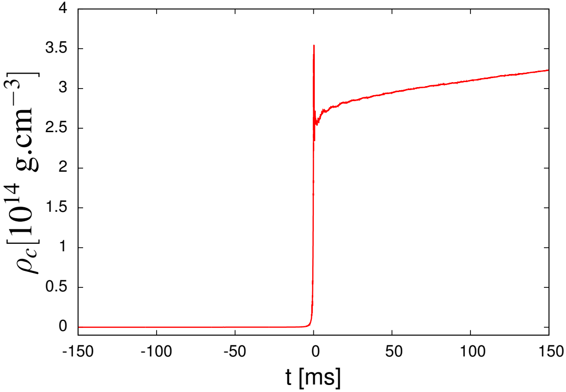


- Massive star
- $\geq 10\ \mathrm{M}_\odot$: iron core
- Iron core reaches the *Chandrasekhar mass*
- Gravitation : mostly baryons n_b
- Pressure : mostly electron degeneracy n_e

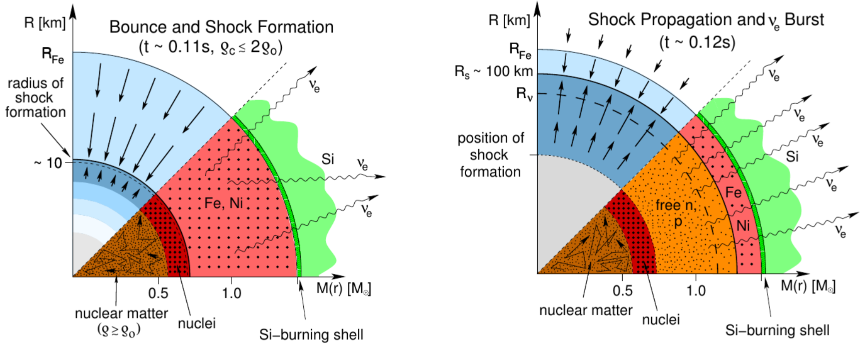
- $p + e^- \rightarrow n + \nu_e$
- n_e decreases $\rightarrow$ pressure decreases
- Neutrinos take away energy

BOUNCE

- Neutrinos trapped
  $\rho \sim 10^{12}$ g.cm^{-3}
- Electron captures $\rightarrow$ equilibrium
- Nuclear interaction becomes very repulsive
  $\rho \sim 10^{14}$ g.cm^{-3}



STANDARD EXPLOSION SCENARIO : SHOCK

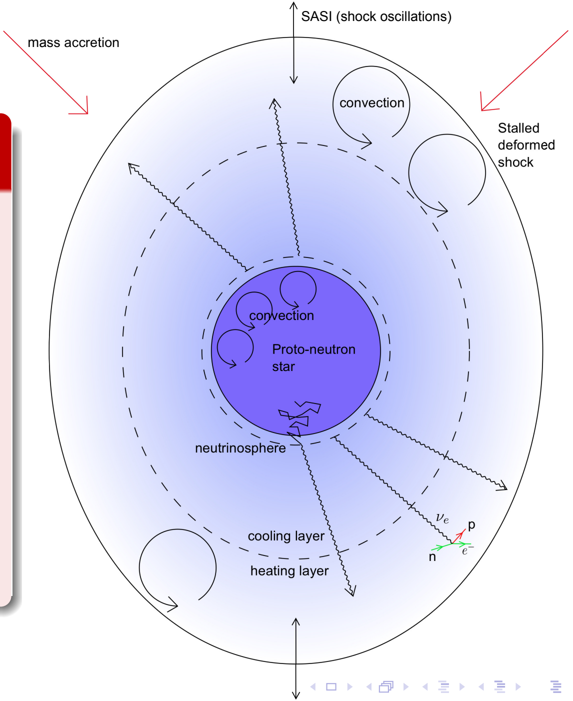


Janka 07

- Proto-neutron star at the center
- The shock is launched and propagates
- Iron photodisintegration and electron capture
- The shock stalls at $r \sim 100\ \mathrm{km}$ from the center
- Mechanism to deposit energy ?

NEUTRINO HEATING MECHANISM

- Huge amount of neutrinos (99% total energy)
- Heat below the stalled shock $\rightarrow$ gives energy $\rightarrow$ shock may recover positive velocities
- If so : explosion ; if not : black hole formation
- Hydrodynamics instabilities



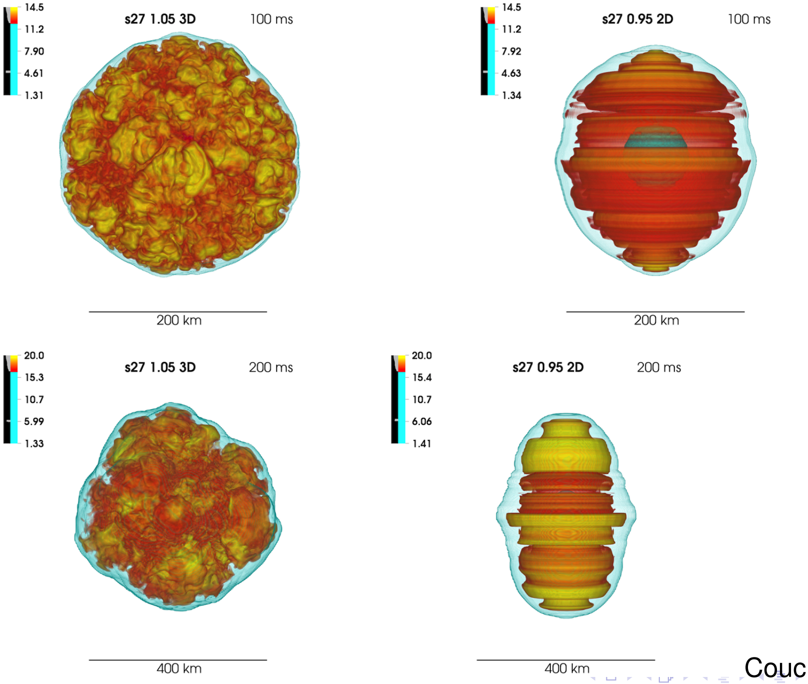
Hydrodynamics instabilities

SASI

- Standing Accretion Shock Instability
- Global deformation of the shock
- Secondary shocks in the gain layer
- Gain layer larger

Small scale convection

- Only very few 3D simulations
- Heating aided by convection explode in 2D (underenergetic $\sim 10^{50}$ ergs of kinetic energy)
- Problematic in 2D ?
- first detailed 3D results did NOT go in the right direction
- anything missing ? maybe too coarse resolution
- High resolution $\rightarrow$ turbulent pressure



Couch *et al.* 13

HOW ACCURATE ARE THEY ?

- 1D hydrostatic (with mixing length for convection)
- non-radial motions in the progenitor ?
- How much stellar winds, mass loss rate ?
- Giant flares (removing some mass, creating anisotropies)
- Few different progenitor sets available

MHD MECHANISM

- Initial magnetic field has to be large ($\sim 10^9$ G)
- Growth during collapse by flux freezing
  $\sim 10^9\ \mathrm{G} \rightarrow \sim 10^{11}\ \mathrm{G}$
- Growth to magnetar-like magnetic fields
  $\sim 10^{11}\ \mathrm{G} \rightarrow \sim 10^{15}\ \mathrm{G}$: magneto-rotational instability ?
- Differential rotation

- The shock stalls and is revived very early, pushed by the very strong magnetic pressure
- Very energetic explosions
- A few percent of progenitor stars
- Uncertainties remaining
  - Magnetic field growth
  - Difference 2D/3D
  - Importance of energy deposition by neutrinos

Neutrino flavor conversion

Heavy lepton neutrinos

- $\nu_x = \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$
- More average energy per neutrino (earlier decoupling with the fluid)
- Cooling of the PNS, minor contribution to heating of the shock

Electron neutrinos

- ν_e, $(\bar{\nu}_e)$
- Less average energy
- Cooling of the PNS, heating of the shock

- *Flavor conversion* due to *neutrino self-interactions* ?
- ν_x deposit energy -> more energetic explosions ?
- Open question, many papers but very simplified settings
- Need for more detailed works

Black hole formation

How to create a black hole

- directly at collapse
- after bounce, the shock stalls and it is not revived soon enough. Matter continues to fall on the PNS and eventually forms a BH
- bounce, stalled shock, shock is revived, explosion, but some matter is not expelled (fallback) and the PNS cools down (possibly SN1987A)

OUTLINE

NUMERICAL SIMULATIONS

Ingredients for a detailed simulation from first principles

- An accurate progenitor
- 3 (spatial) dimensions hydrodynamics
- Nuclear physics based Equation of State
- A precise handling of the gravitation $\rightarrow$ general relativity
- An accurate neutrino treatment $\rightarrow$ a Boltzmann solver
- Extremely demanding in cpu power

NEUTRINOS ARE NOT FLUID

- Mean free path : fully opaque to fully transparent (different from all other particles)
- Decoupling with the fluid $\rightarrow$ fluid treatment not good enough
- Appropriate treatment : transport $\rightarrow$ Boltzmann equation
- Heaviest part and sensitive to small changes

Equations of state

Behavior of matter at some given conditions (n_b, T, Y_e)

- $10^8 \leq m_n n_b \leq 10^{16}$ g.cm^{-3} with n_b the baryon number density
- $0 \leq T \leq 200$ MeV temperature
- $0 \leq Y_e \leq 0.5$ electron fraction ($Y_e = n_e/n_b$)
- Returns thermodynamics quantities : pressure, entropy, abundances, chemical potentials, ...

Nuclear physics based equation of state

- Nucleon–nucleon interaction very hard to model
- Few equations of state available for supernovae
- New EoS coming *e.g.*, Hempel and Schaffner-Bielich, 2010

Contains $n, p, e^-, e^+, \gamma, \alpha, A$

OUTLINE

Relativistic Boltzmann equation

$$\frac{\mathrm{d}x^\mu}{\mathrm{d}\lambda}\frac{\partial f}{\partial x^\mu} - \Gamma^i{}_{\mu\nu}p^\mu p^\nu \frac{\partial f}{\partial p^i} = \mathcal{C}[f]$$

- Derivative of f along a world line
- Gravitation : geodesics equations
  $$\frac{\mathrm{d}p^i}{\mathrm{d}\lambda} + \Gamma^i{}_{\mu\nu}p^\mu p^\nu = 0$$
- $C[f]$: Collision operator
- Neutrinos : null geodesics (considered massless)
- Geodesics between two collisions
- Numerical problems : 6D + time dependence, Lagrangian connection coefficients (include fluid velocity transformations, *e.g.*, doppler shift)
- No 3D hydro + full Boltzmann simulation available

Moments of the Boltzmann equation

$$E(t,\vec{r},\epsilon) = \epsilon \int f(t,\vec{r},\vec{p})\mathrm{d}\Omega$$

$$F^{\alpha}(t,\vec{r},\epsilon) = \epsilon \int l^{\alpha} f(t,\vec{r},\vec{p})\mathrm{d}\Omega$$

- $\mathrm{d}\Omega$: angle in momentum space
- l^{α} normalized 3-momentum
- Flux-limited diffusion
- Two-moments scheme

Collision operator

- Charged current, electron and positron capture
  - $\nu_e + p \leftrightarrow n + e^-$
  - $\nu_e + N(A,Z) \leftrightarrow N(A,Z-1) + e^-$
  - $\bar{\nu}_e + n \leftrightarrow p + e^+$
- Scattering
  - $\nu + p \leftrightarrow \nu + p$
  - $\nu + n \leftrightarrow \nu + n$
  - $\nu + N(A,Z) \leftrightarrow \nu + N(A,Z)$
  - $\nu + e^- \leftrightarrow \nu + e^-$
- Pair processes
  - $e^+ + e^- \leftrightarrow \nu + \bar{\nu}$
  - $N + N \leftrightarrow N + N + \nu + \bar{\nu}$

- Many simplifications
- Simulations extremely sensitive to small changes

OUTLINE

Explosion mechanism

- Neutrino heating
    - Most favored scenario
    - Neutrinos drive the deleptonization
    - Neutrinos drive the cooling of the protoneutron star
    - Neutrinos drive the heating of the shock
    - 2D detailed simulations : underenergetic explosions $\sim 10^{50}$ erg
    - First 3D detailed simulations did not explode
    - Turbulent pressure ?
    - Non-radial instabilities seeded by the progenitor ?
- MHD mechanism : the most energetic supernovae (a few %)
- Equation of state physics improving slowly with constraints from nuclear physics and astrophysics
- Role of neutrino flavor conversion ?

Black hole formation

- Explosion or no explosion ?
- Black hole or neutron star ?
- No single parameter sufficient to discriminate

Numerical treatment of the neutrinos

- Boltzmann equation (radiative transfer problem)
- Full Boltzmann schemes on static background available for comparisons (*e.g.* B.P. *et al.* 2014)
- 3D Hydro + Boltzmann is too heavy for computation
- Approximated transport (LHS) : flux-limited diffusion, two-moments scheme, leakage scheme, light bulb, toy model...
- Approximated collisions (RHS) : elastic scattering, mean heavy nuclei, ...