Formation of the central engine of Long GRBs

Miguel A. Aloy
ERC Fellow
Departamento de Astronomía y Astrofísica

collaborators
N. DeBrye, C. F. Cuesta-Martínez, M. Obergaulinger, P. Cerdá-Durán, P. Mimica, J. A. Font

(Cerdá-Durán+’13, arXiv:1310.8290)
LGRB Progenitors: Collapsars

Woosley (1993):
- Collapse of a massive (M ~ 30M☉, WR) rotating star that does not form a successful SN but collapses to a BH (M_BH ~ 3M☉) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.

Caveats:
- Rapidly spinning stars produce low rotating cores due to magnetic torques (Spruit’02, Heger+’05)

Solutions:
- Low metallicity + strong rotation ⇒ chemically homogeneous evolution ⇒ cores retain high spin (Yoon& Langer’05, Woosley & Heger’06, Yoon+’06)
- Interacting binaries

Outcomes:
- LGRB?
- SNe / Unnovae?
- BH or proto-magnetar?
LGRB Progenitors: Collapsars

If the progenitor forms a collapsar:

- The viscous accretion onto the BH $\Rightarrow$ strong heating $\Rightarrow$ thermal $\nu\nu$-annihilating preferentially around the axis $\Rightarrow$ formation of a relativistic jet ($\Gamma>10$)?.

- Numerical models: ultrarelativistic outflow can form if luminosity $> L_{th} \sim 10^{49} \text{ erg}$

- Numerical simulations: core-collapse, rapid rotation, computing GW and other aspects of the problem:
  Shibata'00,'03, Dimmelmeier'02,'07,'08, Fryer'04, Cerdá-Durán'05,'07, Dessart'08, Kiuchi'09, Kotake'09,'11, Scheideger'10, Sekiguchi'11, O'Connor'10,'11, Ott'11,'13...
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the code

- **General relativity:**
  - ★ spectral methods (LORENE library)
- **Godunov-type schemes for hydrodynamics.**
- **Spherical polar coordinates:**
  - ★ \( \Delta r = 200 \text{ m} \) (innermost 20 km)
  - ★ logarithmic grid for \( r > 20 \text{ km} \) -> \( \Delta r \sim 800 \text{ m} \) at 100 km
  - ★ outer boundary 30000 km
  - ★ \( \Delta \theta = 1.4^\circ \)
- **Axisymmetry (2D) + equatorial symmetry**
- **EOS:** Lattimer & Swesty’91 + Timmes & Arnett’99 (table by O’connor & Ott 2010, LS220 in this work)
- **GW:** quadrupole formula (good approx. in PNS: Reisswig et al 2010)
- **Neutrino leakage scheme** (De Brye et al in prep)
The main focus of our models is not an accurate determination of whether a particular star develops an explosion due to neutrino heating, but specifically an exploration of the consequences of a fSN, in which neutrino heating does not stop the mass accretion and thereby prevent the collapse of the inner core to a BH.

Thus, very high accuracy in the neutrino physics is only of secondary relevance here and we can employ simple, fast approximations for the neutrino physics.
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neutrino treatment: leakage

— Energy averaged: Fermi distribution

• inside ⇒ thermal + beta eq. ⇒ \( \eta = \eta_{\text{eq}}, \ T_\nu = T_{\text{fluid}} \)
• outside ⇒ neutrinos scape ⇒ \( \eta = 0, \ T_\nu = T_\nu\text{-sphere} \)

— Neutrinosphere = \( \tau \) threshold ⇒ ray-by-ray in radial direction

— Neutrinosphere-opacity loop (computationally expensive):

\[ \text{chemical potential} \rightarrow \text{opacity} \rightarrow \text{optical depth} \rightarrow \text{neutrinosphere location} \rightarrow \text{chemical potential} \]

NOTE: loop can be avoided by fixing beta-equilibrium everywhere (e.g. Sekiguchi’11)
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neutrino treatment: leakage

- Diffusion region: rates based on optical depth

\[ \mathcal{Q}_{\nu_i}^{\text{diff}} \propto \frac{1}{t_{\nu_i}^{\text{diff}}} \]  
\[ t_{\nu_i}^{\text{diff}} \propto kT_{\nu_i}^{\text{diff}} \]

- Effective rates: \textit{Harmonic mean} of diffusion and free streaming rates

\[ E_{\nu_i}^{\text{diff}} = \frac{Q_{\nu_i}^{\text{diff}}}{R_{\nu_i}^{\text{diff}}} \]  
\[ \frac{1}{E_{\nu_i}^{\text{eff}}} = \frac{1}{E_{\nu_i}^{\text{diff}}} + \frac{1}{E_{\nu_i}^{\text{free}}} \]  
\[ \frac{1}{R_{\nu_i}^{\text{eff}}} = \frac{1}{R_{\nu_i}^{\text{diff}}} + \frac{1}{R_{\nu_i}^{\text{free}}} \]  
\[ Q_{\nu_i}^{\text{eff}} = R_{\nu_i}^{\text{eff}} E_{\nu_i}^{\text{eff}} \]

Includes a free parameter

\[ k=0.5 \implies \text{Ruffert, Janka & Schaffer'96} \]  
\[ \text{Rosswog & Liebendörfer'03} \]  
\[ \text{Cerdá-Durán et al.'13} \]  
\[ k=1.0 \implies \text{O’Connor & Ott (2011)} \]
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neutrino treatment: leakage

– Three neutrino species: $\nu_e$, $\bar{\nu}_e$ and $\nu_X$

– Neutrino emission:
  • $\beta$-processes: $e^- + p \rightarrow n + \nu_e$ ; $e^+ + n \rightarrow p + \bar{\nu}_e$
  • thermal pair annihilation: $e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i$
  • plasmon decay: $\gamma \rightarrow \nu_i + \bar{\nu}_i$

– Neutrinos diffusion:
  • absorption: $n + \nu_e \rightarrow e^- + p$ ; $p + \bar{\nu}_e \rightarrow e^+ + n$
  • scattering: $\nu_i + N \rightarrow \nu_i + N$ ; $N \in \{p, n, A\}$

– Inelastic scattering: cannot be implemented in a leakage scheme (relevant before bounce). Alternatives:
  • Simple deleptonization scheme (Liebendörfer 2005)
  • Own deleptonization tables: 1D Simulations, multi-energy, hyperbolic 2-momentum eqs. for $\nu$–transport (Obergaulinger & Janka 2013; Obergaulinger et al. 2013)

(see talk by O. Just on Friday)
Comparison with Liebendörfer et al 2005 (G15 model)
Model: 35OC of Woosley & Heger 2005
(Wolf-Rayet star, $\Omega_c \sim 2 \text{ rad s}^{-1}$), EOS: LS220

$\nabla \rho / \rho$  \hspace{1cm} time = 841.152 ms

HD grid: [100 (unif.) + 1100 (log)] x 64
LORENE: 17 domains x (17 x 9)

Wind lost: \hspace{0.5cm} 7 M\odot
Fe core: \hspace{0.5cm} 2.02 M\odot
Evolve: \hspace{0.5cm} 22 M\odot
Typical conditions after bounce inside the shock:
\( t - t_b \sim 0.5 \text{ s}, \) equatorial profile

![Graph showing the typical conditions after bounce inside the shock. The graph illustrates the entropy per baryon, electron-neutrinosphere, and accretion shock. Key labels include inner core, PNS, hot bubble, convectively stable, and electron-neutrinosphere.](image)
**Time evolution of the baryonic mass**

- $\bar{M}_{\text{bar}}^\text{shock}$ dominated by the OC initial density profile.

- $t_{\text{dwell}} \ll t_{\text{BH}} \sim 1.6 \text{ s}$

- $\bar{M}_{\text{bar}}^\text{shock}$ dominated by the deleptonization cooling matter outside the shock.

- $t = 220 \text{ ms}$

- $M_{\text{BH}}^0 \sim 2.7 M_\odot$

- $\dot{M}_{\text{bar}}^\text{shock} = 0.45 M_\odot \text{s}^{-1}$ up to $\sim 100 \text{ ms}$.

- $\bar{M}_{\text{bar}}$ as a function of $t - t_{\text{bounce}}$ in [ms].

- Inside shock, inside PNS, inside inner core.

- Iron core accreted at $t = 120 \text{ ms}$. 
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limitations of our treatment

— The thermal structure and the rotation profile of the PNS evolves from the $t_b$ to $t_{BH}$

$\Rightarrow M_{BH}^0$ and $t_{BH}$ depend on the evolution of the PNS, including the cooling by neutrinos diffusing out of the PNS and the angular momentum redistribution.

• The presence of strong B-fields, due to the MRI, or non-axisymmetric instabilities will probably enhance the transport of angular momentum, decreasing the $M_{BH}^0$ and $t_{BH}$.

• **Non-magnetized axisymmetric simulations provide an upper limit to the $t_{BH}$**.

• Lower limit estimate for $t_{BH}$: time at which $2.41 \, M_\odot$ have accreted through the shock, $t_{BH}^{\text{min}} - t_b \sim 820 \, \text{ms}$.

• Using a stiffer EoS would allow for larger maximum masses and hence longer collapse times.
Gravitational wave spectrum

$10^{-19}$

$10^{-20}$

$10^{-21}$

$10^{-22}$

$10^{-23}$

$10^{-24}$

$h_{\text{char}}$

$f [\text{Hz}]$

D=100 kpc

- fiducial model

- - slow rotation

D=15 Mpc

- - fiducial model

- - slow rotation

Adv. LIGO

Adv. VIRGO

KAGRA

ET

fiducial model

slow rotation
Spectrogram analysis

Complex spectrogram, whose analysis is done by identifying frequencies and regions where this frequencies are produced (i.e., with the help of other spectrograms of, e.g., density, shock position, etc.)
Buoyancy frequency

\[ N^2 = \left( \frac{\nabla \rho}{\rho} - \frac{\nabla P}{\Gamma_1 P} \right) \cdot g \]  

Brunt-Väisälä frequency

\[ N^2 > 0 \]  

Convectively stable (Ledoux criterion)

- Local linear stability analysis (non-rotating, non-relativistic)

- Caveats:
  - Rotating star: Solberg-Høiland criteria (work in progress...)
  - General relativity (Müller et al 2013)
Spectrogram analysis.

Buoyancy frequency

Postshock/PNS convection excites g-modes at the lower boundaries of the unstable regions.

\[ f_{g,\text{PNS}} \sim \frac{\sqrt{N_{\text{turn}}^2}}{2\pi} \sim \frac{1}{2\pi} \frac{GM_{\text{PNS}}}{R_{\text{PNS}}^2} \sqrt{\frac{(\Gamma - 1)m_n}{\Gamma k_B T}} \left( 1 + \frac{GM_{\text{PNS}}}{2c^2 R_{\text{PNS}}} \right)^{-4} \]

(Murphy et al 2009, Müller et al 2013)

Outer stable layer:
- \( \sim 100 \text{ Hz after bounce} \)
- monotonically increasing frequency to a few \( \text{kHz} \)
- contraction+\( \nu \)-cooling

\[ \Gamma = \frac{4}{3} \]
\[ k_B T = 15 \text{ MeV} \]
Avoided crossing of modes

During the rise: quadrupolar velocity patterns.

During the drop: quasi-radial velocity pattern. Since $f_{qr} \rightarrow 0$ $\Rightarrow$ unstable mode $\Rightarrow$ BH formation (Chandrasekhar’64)

Change in behaviour of this feature likely due to an avoided crossing of two modes:

i. g-mode (inner convectively stable layer)
$$f_{g,c} \sim \frac{1}{2\pi} \frac{GM_{1C}}{R_{1C}^2} \sqrt{\frac{1}{\Gamma} \frac{\Delta s}{s}} \left(1 + \frac{GM_{1C}}{2c^2 R_{1C}}\right)^{-4} \text{kHz}$$

ii. qr-mode with decreasing frequency
$$f_{qr} \sim 3.3 \left(\log \frac{\rho_{c,BH}}{\rho_c}\right)^{1/2} \text{kHz}$$

Avoided crossings have been observed:

- Numerically: in NSs around its maximum mass (Gourgoulhon et al. 1995; Galeazzi et al. 2013).
- Perturbation analysis: radial- and f-modes (Gondek et al. 1997; Kokkotas & Ruoff 2001) and crustal-modes (Gondek & Zdunik 1999).
GW

Shock radius at equator

Signature of SASI on the gravitational waves
- Observed from the neutrino-sphere to the shock location
- Sound waves confined in a cavity
- Multiple overtones
Spectrogram analysis

D: f-mode excited at bounce. Highly damped by sound waves in the hot bubble

\[ f_f \sim 0.78 + 1.635 \sqrt{\frac{M_{\text{PNS}}}{1.4 M_\odot}} \left( \frac{10 \text{ km}}{R_{\text{PNS}}} \right)^3 \text{ kHz} \]

(Andersson & Kokkotas’98)

\[ t - t_{\text{bounce}} [\text{ms}] \]

\[ f [\text{kHz}] \]

quasi-radial mode

f-mode (excited @ bounce)

g-modes at surface PNS

g-modes in cold IC

SASI motions hitting the surface of the PNS

D h x [cm]

\(10^\bullet\text{km}\)
Detectability

• How many massive, fast-rotating stars, with Z\(<\) Z⊙ produce fSNe?

• Active matters of debate:
  • fraction of massive stars producing BHs / NSs?
  • channels for BH formation?
  • observational signatures? (e.g., Lovegrove & Woosley'13; Piro'13).

• Hard to estimate the rate, R_mfr.
  • They can be a sizable fraction of the fSNe.
  • Rate of fSNe \sim 10% of CCSNe (Woosley+'12).
  • 1D-pistons (no rotation / binary effects) \Rightarrow \sim 25% (Zhang+08; Ugliano+'12).

• SN rate problem: SN rate predicted from the star formation rate is higher than the SN rate by observations.
  • In local Universe (\leq 10 Mpc), the rate of dim CCSNe is high (\sim 30\%−50\%);
  \Rightarrow a fraction of them are CC events producing BHs (Horiuchi+'11).
  • Paucity of observed high mass RSGs in 16.5M⊙ \leq M \leq 25M⊙ can be explained if they are fSNe. fSNe rate \leq 20% of CCSN \Rightarrow \sim 0.2 y^{-1} (Kochanek'13).
  • 10\%−50\% of massive MS stars are fast rotators (\leq 200 km s^{-1}; Mink+'13).

\Rightarrow Fast spinning, moderate-Z, massive stars happening in nearby galaxies, might bring detectable GW signals for the Einstein Telescope at rates of \leq 0.1 y^{-1}.
Conclusions

• The PNS phase in the collapsar scenario is optimal for GW emission:
  - large amplitude: visible with ET in the Virgo cluster
  - long duration: ~ seconds
  - quasi-periodic signal
  - possible EM signal: long GRB, SN

• It may provide information about the conditions in the PNS
  - size of PNS
  - contraction/accretion time-scale
  - cooling time-scale
  - rotation
  - SASI

• Detectability: prospects for ~0.1 yr⁻¹ with Einstein Telescope.