SIMULATIONS OF STELLAR COLLAPSES TO BLACK HOLES: INFLUENCE OF HYPERONS

Jérôme Novak (Jerome.Novak@obspm.fr)

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris / Université Paris-Diderot

Peres, Oertel & Novak,
Phys. Rev. D **87**, 043006 (2013)

Supernovae & Gamma-Ray Bursts 2013, YITP Kyoto University, October, 15th 2013

Plan

1. Numerical model
2. Equation of state
3. Parameters
4. Results

Plan

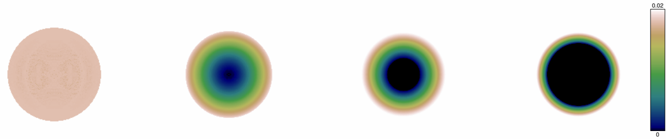
1. Numerical model
2. Equation of state
3. Parameters
4. Results

Plan

Plan

- Stellar-mass black holes form in the collapse of massive stars
- Beginning of collapse triggered by mass-limit of iron core
- Collapse & bounce, then collapse of the proto-neutron star triggered by accretion

⇒very similar scenario to core-collapse supernova
⇒central engine for gamma-ray bursts (collapsar model)

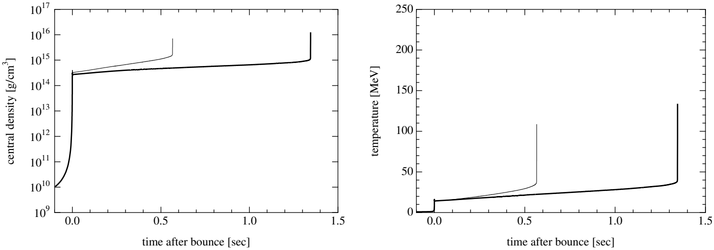


bolometric luminosity

Vincent *et al.* (2012)

Context

Collapse to black hole from stellar progenitor has already been studied (*e.g.* Sumiyoshi *et al.* (2007), Fischer *et al.* (2009), O'Connor & Ott (2011), Ugliano *et al.* (2012)...).



$40M_\odot$ progenitor, from Sumiyoshi *et al.* (2007)

$\Rightarrow$much higher densities (above nuclear saturation density) and temperatures (tens of MeV) than in supernova simulations.

Aims. . .

High density & temperature conditions $\Rightarrow$additional particles should appear (observed on Earth).

- How many "exotic" particles could appear on the way to the black hole?
- What is their influence on the collapse?
- What is their observational signature? (neutrinos, gravitational waves)

Reverse question:

- Can we infer nuclear matter composition from observations of black hole formation?

LIGO

Virgo

KAGRA

Numerical model

Physical framework

- Spherical or axial symmetry (1D/2D runs).
- Relativistic hydrodynamics, with perfect-fluid stress-energy tensor.
- General relativity in 3+1 formulation. Isotropic gauge for 1D, conformally-flat condition (CFC) in 2D.
- Apparent horizon finder (Lin & Novak 2007).
- Microphysical equation of state from Oertel *et al.* (2012).
- Deleptonization and neutrino leakage.
- Gravitational waves extracted with the modified quadrupole formula (2D).

Numerical tools

CoCoNuT code (Dimmelmeier *et al.* 2005):

- Potentially 3D code, but used only in 1D or 2D (not fully parallel, yet);
- high resolution-shock capturing schemes for the relativistic hydrodynamics (*e.g.* Font 2008)⇒conservative-form hydrodynamic equations;
- multi-domain pseudo-spectral methods for the solution of Einstein equations (*e.g.* Grandclément & Novak 2009) ⇒non-linear coupled elliptic system;
- interpolation and filtering to avoid Gibbs phenomenon.

Neutrino leakage

- Only one opaque (⇒fluid) zone and one transparent (⇒free-streaming) zone (*e.g.* van Riper *et al.* 1981)
- No transport, cheap in CPU time, but number of approximations and drawbacks
- No semi-transparent regime, no self-consistent heating ⇒not good to revive the shock.

⇒computation of "optical" depth for three species of neutrinos: $\nu_e, \bar{\nu}_e, \nu_x$. Loss of energy & momentum taken into account.

Creation processes

- $p + e^- \to \nu_e + n$
- $(A, Z) + e^- \to (A, Z-1) + \nu_e$
- $e^- + e^+ \to \nu_i + \bar{\nu}_i$
- $\tilde{\gamma} \to \nu_i + \bar{\nu}_i$

Opacity processes

- $\nu_i + N \to \nu_i + N$
- $\nu_i + (A, Z) \to \nu_i + (A, Z)$
- $\nu_e + n \to p + e^-$
- $\bar{\nu}_e + p \to n + e^+$

UTH

Equation of state

Nuclear model

Nucleon - nucleon interaction uncertain and difficult to model: use different interactions.

Model by Lattimer & Swesty (1991)

- Effective (Skyrme-type) model for the nucleon-nucleon interaction
- Constituents: $n, p, e^-, e^+, \gamma, \alpha, A$
- Incompressibility $K = 220$ MeV.

$\Rightarrow$ other parameters involved: B, J, K', L, constrained by nuclear experiments, but defined at saturation density n_0 and for symmetric matter.
$\Rightarrow$ one of the two mainly used EoSs, other: Shen *et al.* (1998), based on a relativistic mean field model.

Additional particles

Oertel *et al.* (2012), Gulminelli *et al.* (2012)

Particle accelerators and heavy-ion colliders show the presence of pions and hyperons at high densities and temperatures.
$\Rightarrow$ these "additional" particles should appear in core-collapse phenomena

EoS LS220+pions

- Pions π^-, π^0, π^+
- free gas

EoS LS220+hyperons

- Λ hyperons
- interactions adapted from Balberg & Gal (1997)
- contains a first order phase transition to hyperonic matter

Hadronic interaction different from previous studies with additional particles (Sumiyoshi *et al.* 2009, Shen *et al.* 2011), where a relativistic mean field model was used.

Neutron star mass constraints

- Classical result: with hyperons, maximum neutron star mass $\sim 1.4 M_\odot$.

$\Rightarrow$ Absolutely incompatible with observations :

Mass constraint

- $M = 2.01 \pm 0.04\ \mathrm{M}_\odot$ Antoniadis *et al.* (2013)
- $M = 1.97 \pm 0.04\ \mathrm{M}_\odot$ Demorest *et al.* (2010)

Solutions:

- Stiffen (modify) the EOS, with short-range repulsion via YY interaction
- Let quarks appear early enough...

In our cases, static neutron stars computed with $T = 0$ and β-equilibrium:

- EoS LS220+pions maximal mass: $M = 1.95\ M_\odot$
- EoS LS220+hyperons maximal mass: $M = 1.91\ M_\odot$

Parameters & Initial models

Initial setup

Progenitor

- From Woosley *et al.* (2002), $40M_\odot$ ZAMS and $10^{-4}\times$ solar metallicity

Leakage

- β-equilibrium density 1.2×10^{12} g.cm^{-2}
- ν escape time $t_{esc} = 3(R_{\nu-\text{sphere}} - r)\tau$
- power lost by the fluid in the trapped regime $Q_E = -1.1\,\langle\epsilon_\nu\rangle\,\dfrac{Y_\nu}{t_{esc}}$

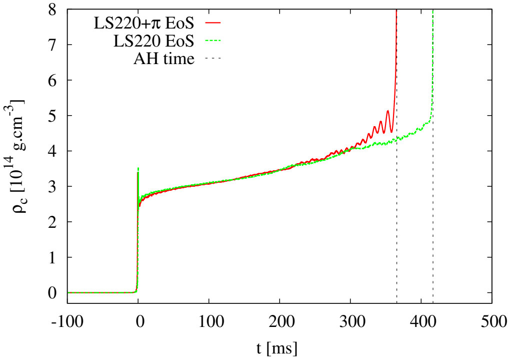
EoS

- Values of the parameters for $Y-N$ and $Y-Y$ interactions compatible with hyperonic data and PSR J 1614-2230 (marginally).

Black hole formation

Spherical symmetry

with pions

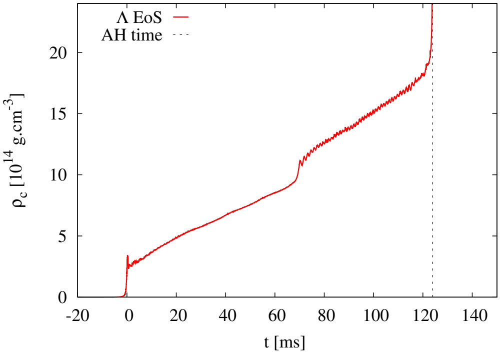


- Maximum pion fraction $Y_{\pi^-} = 0.13$ at the onset of BH collapse
- $Y_{\pi^-} > Y_{\pi^0} > Y_{\pi^+}$ at all times

- The PNS with LS220+π EoS is slightly more compressible
- More compressible means less pressure $\rightarrow$ cannot hold as much mass as LS220 $\rightarrow$ less time post bounce accreting mass and maximum mass smaller
- PNS baryonic masses at BH collapse : $2.55\ M_\odot$ with LS220, $2.49\ M_\odot$ with LS220+π

Spherical symmetry

with hyperons

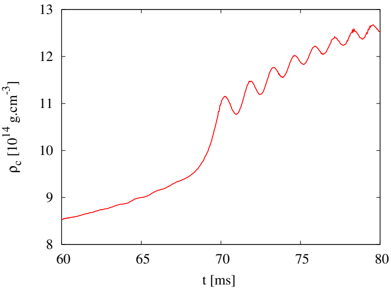


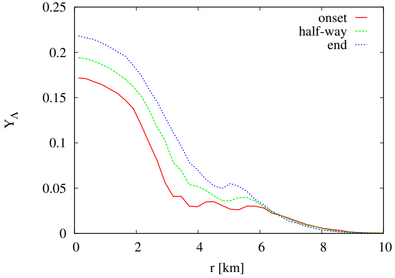
- PNS baryonic mass at BH collapse : 2.00 $M_\odot$
- Maximum of Λ hyperon fraction $Y_\Lambda = 0.41$ at the onset of BH collapse

- Presence of a phase transition to hyperonic matter (related to the high accretion rate)
- The PNS oscillates after the phase transition (PNS fundamental modes)
- Oscillations are resolved in time and stay when increasing the resolution

Phase transition

Spherical symmetry



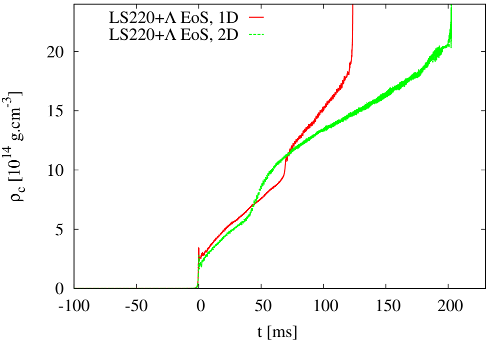


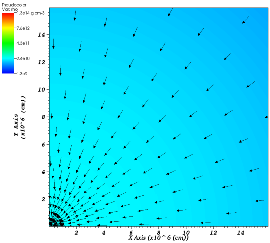
- Phase transition only reached for progenitors with high mass accretion rate (low metallicity),
- Induces a "mini-collapse" followed by oscillations of the PNS,
- No second shock wave as in simulations with phase transition to quark matter (Sagert *et al.* 2009).

Phase transition

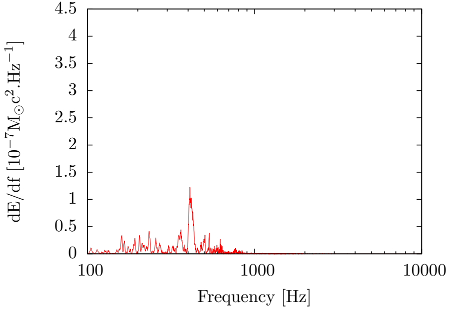
Rotational symmetry

- 2D in axisymmetry
- Progenitor rotation profile : slow and differential
- All other settings similar to 1D settings



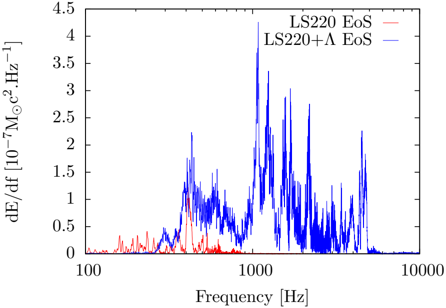


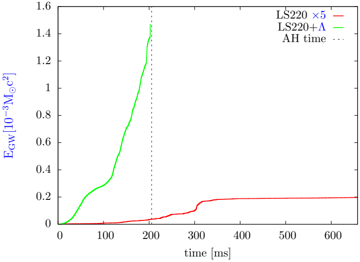
With the modified quadrupole formula



Gravitational waves

With the modified quadrupole formula





Phase transition induces higher frequency and higher amplitude waves

Summary / Outlook

- EoS for core-collapse based on Lattimer & Swesty (1991), with additional particles (π, Λ), compatible with recent observations of $2M_\odot$ neutron stars.
- Softens the PNS, which collapses more rapidly and eventually undergoes a phase transition to hyperonic matter.
- Phase transition "softened" in 2D simulations $\Rightarrow$implications for QGP phase transition?
- Possibly observable with gravitational waves.

- Improvement of resolution in 2D
- Better (full?) neutrino transport (Peres *et al.* `arXiv:1307.1666`)

Summary / Outlook

- EoS for core-collapse based on Lattimer & Swesty (1991), with additional particles (π, Λ), compatible with recent observations of $2M_\odot$ neutron stars.
- Softens the PNS, which collapses more rapidly and eventually undergoes a phase transition to hyperonic matter.
- Phase transition "softened" in 2D simulations $\Rightarrow$implications for QGP phase transition?
- Possibly observable with gravitational waves.

- Improvement of resolution in 2D
- Better (full?) neutrino transport (Peres *et al.* `arXiv:1307.1666`)

References

- Antoniadis, J. *et al.*, Sience **340**, p.448 (2013)
- Balberg, S. and Gal, A., Nucl. Phys. A **625**, p.435 (1997)
- `http://www.mpa-garching.mpg.de/hydro/COCONUT`
- Demorest, P. *et al.*, Nature **467**, p.1081 (2010)
- Dimmelmeier, H. *et al.*, Phys. Rev. D **71**, 064023 (2005)
- Fischer, T. *et al.*, Astron. Astrophys. **499**, 1 (2009)
- Font, J.A., Living Rev. Relat. **11**, 7 (2008)
- Grandclément, P. and Novak, J., Living Rev. Relat. **12**, 1, (2009)
- Gulminelli, F *et al.*, Phys. Rev. C **86**, 025805 (2012)
- Lattimer, J.M. and Swesty, F.D., Nucl. Phys. A **535**, p.331 (1991)
- Lin, L.-M. and Novak, J., Classical Quantum Gravity **24**, p.2665 (2007)
- O'Connor, E. and Ott, C.D., Astrophys. J. **730**, p.70 (2011)
- Oertel, M. *et al.*, Phys. Rev. C **85**, 055806 (2012)
- Peres, B. *et al.*, Phys. Rev. D **87**, 043006 (2013)
- Peres, B. *et al.*, `arXiv:1307.1666`
- Sagert, I. *et al.*, Phys. Rev. Lett. **102**, 081101 (2009)
- Shen, H. *et al.*, Nucl. Phys. A **637**, p.435 (1998)
- Shen, H. *et al.*, Astrophys. J. Suppl. Ser. **197**, p.20 (2011)
- Sumiyoshi *et al.*, Astrophys. J. **667**, p.382 (2007)
- Sumiyoshi *et al.*, Astrophys. J. Lett. **690**, L43 (2009)
- Ugliano *et al.*, Astrophys. J. **757**, p.69 (2012)
- van Riper, K.A. and Lattimer, J.M., Astrophys. J. **249**, p.270 (1981)
- Vincent, F.H. *et al.*, Classical Quantum Gravity **29**, 245005 (2012)
- Woosley *et al.*, Rev. Mod. Phys. **74**, p.1015 (2002)