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Core Collapse supernova simulations with a new hyperon equation of state compatible with two solar mass neutron star

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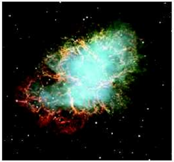
Plan of the Talk

- Introduction
- Microphysics: Role of hyperon equation of state (EoS)
- Core Collapse Supernova (CCSN) Simulations
- Summary and Outlook

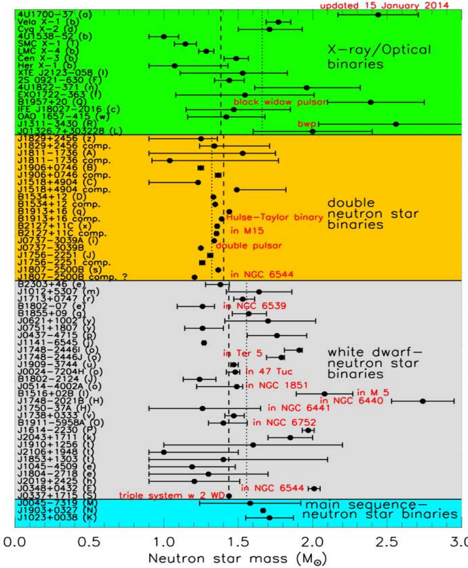


Understanding the final journey of a massive star after its fuel has been exhausted is a challenging problem. The outcome is a core collapse supernova and the residue may take the form of either a neutron star or a black hole.

Colgate et al., Astronomical Journal 70 (1961)

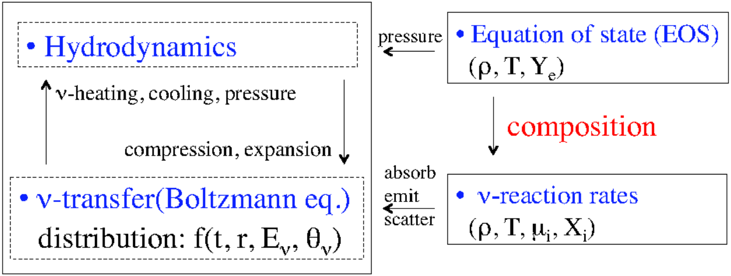
- Accurately measured highest Neutron Star mass is $2.01 \pm 0.04_{\odot}$. [J. Antoniadis et al., Science 340 (2013)]
- Does exotic matter (hyperon, Bose condensates, quarks) exist in NS?
- Exotic EoS should satisfy the constraint $M_{max}^{theo} > M^{obs}$.

[Lattimer (2014)]



Numerical simulation of supernovae

Combination of hydrodynamics with neutrino transfer



- Initial condition: Fe core of massive stars (ex. $15M_{sun}$)
- Follow gravitational collapse & bounce, shockwave,....

Equation of state (EoS) is an important microphyics input. For simulations of stellar collapse, we need EoS with wide ranges of

- density ($10^3 - 10^{15}\mathrm{g/cm}^3$),
- temperature ($0 - 150$MeV)
- proton fraction ($0 - 0.6$).

Most of the EoS for SN simulations are composed of non-strange particles like neutrons, protons, α-particles and heavy nuclei. Those nuclear EoS satisfy $2M_\odot$ constaint.

Supernova EOS covering the wide range

- Parameterized EOS for systematic studies
  - Baron-Cooperstein, Takahara-Sato, Bruenn, Swesty, … (1980~)
- Supernova EOS in numerical simulations
  - Lattimer-Swesty EOS (1991) — LS-EOS
    - *Extension of liquid-drop models (Skyrme-like)*
  - H. Shen, Toki, Oyamatsu & Sumiyoshi EOS (1998)
    - *Relativistic Mean Field approach* — Shen-EOS
- Recent developments
  - Mixture of nuclei
    - Hempel & Schäffner-Bielich (2010), Botvina, Blinnikov, Furusawa
  - Extension of mean fields (+strangeness, quarks)
    - G. Shen-Horowitz (2011)
    - Ishizuka (2006), Nakazato (2008), Sagert (2009)

Novel phases of dense matter might be possible in the post-bounce phase of a core-collapse supernova

- Strangeness may appear in the form of
- Hyperons,
- Bose-Einstein condensates of Kaons,
- Quarks.
- A strong signature of quark-hadron phase transition was predicted during the post-bounce phase.[Ref:I. Sagert et. al. PRL102, 2009]
- Can phase transitions from nuclear to other exotic matter trigger supernova explosions?

- Hyperons produced at the cost of the nucleons.

$$n + p \longrightarrow p + \Lambda + K^0, \quad n + n \longrightarrow n + \Sigma^- + K^+$$

- Chemical equilibrium in compact star interior through weak processes,
- $p + e^- \longrightarrow \Lambda + \nu_e, \quad n + e^- \longrightarrow \Xi^- + \nu_e$
- Condition for chemical equilibrium

$$\mu_i = b_i \mu_n - q_i \mu_e$$

- Threshold Condition for Hyperons

$$\mu_n - q_i \mu_e \geq m_B^* + g_{\omega B}\omega_0 + g_{\rho B}\rho_{03}\tau_3$$

- Λ hyperons, being the lightest hyperons with an attractive potential of ~ -30 MeV in nuclear matter, are believed to populate the dense matter first among all strange baryons.
- Threshold Condition for Λ hyperons $\mu_n = \mu_\Lambda$
- Other hyperons, Ξ & Σ are excluded due to their relatively higher threshold and lack of experimental data.
- Recently Shen et. al extended their nuclear EoS to include Λ hyperons [Ref:Shen et al. ApJ197 (2011)]
- Michaela Oertel and collaborators also constructed hyperon EoS [Ref: M. Oertel et al. PRC85 (2012)]
  Those hyperon EoS are not compatible with a $2M_\odot$ neutron star

New Hyperon EoS

- should satisfy the experimental constraint on the value of parameter (L) corresponding to the density dependence of the symmetry energy
- should be consistent with $2M_\odot$ neutron star

- We construct the hyperon EoS tables for densities ($10^3 - 10^{15}\mathrm{g/cm}^3$), temperatures ($0.1 - 158\mathrm{MeV}$) and proton fractions ($0.01 - 0.6$).

- We adopt a Density Dependent Relativistic Mean Field (RMF) Model to describe uniform matter including hyperons

- At low temperature and sub-saturation density, matter is mainly composed of light and heavy nuclei coexisting with unbound nucleons. This is treated in the Nuclear Statistical Equilibrium model (Saha Equation) (Hempel and Schaffner, Nucl. Phys. A837, 210 (2010)).

- Density Dependent Relativistic Model: The interaction between baryons is mediated by the exchange of scalar (σ) and vector (ω, ϕ, ρ) mesons.
- The Lagrangian density for baryons is given by

$$
\begin{aligned}
\mathcal{L}_B = & \sum_{B=N,\Lambda} \bar{\Psi}_B \left(i\gamma_\mu \partial^\mu - m_B^* - g_{\omega B}\gamma_\mu \omega^\mu - g_{\phi B}\gamma_\mu \phi^\mu \right. \\
& \left. - g_{\rho B}\gamma_\mu \boldsymbol{\tau}_B \cdot \boldsymbol{\rho}^\mu \right) \Psi_B \\
& + \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) \\
& - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu \\
& - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu} \cdot \boldsymbol{\rho}^{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu .
\end{aligned}
$$

Ref: S. Banik, M. Hempel, D.B. , ApJS214 (2014) 22; S.Banik, D.B., Phys.Rev. C66 (2003) 065801

The thermodynamic potential per unit volume for nucleons is given by

$$\frac{\Omega_B}{V} = \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}m_\omega^2\omega_0^2 - \frac{1}{2}m_\phi^2\phi_0^2 - \frac{1}{2}m_\rho^2\rho_{03}^2 - \Sigma^r \sum_{i=n,p,\Lambda} n_i$$
$$-2T\sum_B \int \frac{d^3k}{(2\pi)^3}[ln(1+e^{-\beta(E^*-\nu_B)}) + ln(1+e^{-\beta(E^*+\nu_B)})] \,.$$

Here, $\beta = 1/T$, $E^* = \sqrt{(k^2 + m_B^{*2})}$ and Σ^r is the rearrangement term.

$$P_B = -\Omega_B/V.$$

The energy density is given by,

$$\epsilon_B = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\phi^2\phi_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2$$
$$+2\sum_B \int \frac{d^3k}{(2\pi)^3}E^*\left(\frac{1}{e^{\beta(E^*-\nu_B)}+1} + \frac{1}{e^{\beta(E^*+\nu_B)}+1}\right) \,.$$

Parameters of the Model

- The density dependent couplings (DD2 parameter set) $g_{\sigma N}$ and $g \omega N$ are given by

$$g_{\alpha N} = g_{\alpha N}(n_0) f_\alpha(x)$$
$$f_\alpha(n_b/n_0) = a_\alpha \frac{1 + b_\alpha (x + d_\alpha)^2}{1 + c_\alpha (x + d_\alpha)^2}$$

  Here n_0 is the saturation density, $\alpha = \sigma, \omega$ and $x = n_b/n_0$.
- For ρ mesons, $g_{\rho N} = g_{\rho N}(n_0) exp[-a_\rho (x - 1)]$.
- The scaling factors for vector and isovector mesons from the SU(6) symmetry relations of the quark model
  $\frac{1}{2} g_{\omega \Lambda} = \frac{1}{3} g_{\omega N}$; $g_{\rho \Lambda} = 0$; $2 g_{\phi \Lambda} = -\frac{2\sqrt{2}}{3} g_{\omega N}$
- Scalar-Λ hyperon is obtained from the potential depth of Λ hyperon in saturated nuclear matter: $U_\Lambda^N(n_0) = \Sigma_\Lambda^v - \Sigma_\Lambda^s$
- The potential depth $U_\Lambda^N(n_0) = -30$ MeV from Λ hypernuclei data.

Extended NSE model

Internal excitations, Coulomb screening and excluded volume effects are included.

The total canonical partition function is given by,

$$Z(T,V,\{N_i\}) = Z_{nuc} \prod_{A,Z} Z_{A,Z} \; Z_{Coul}.$$

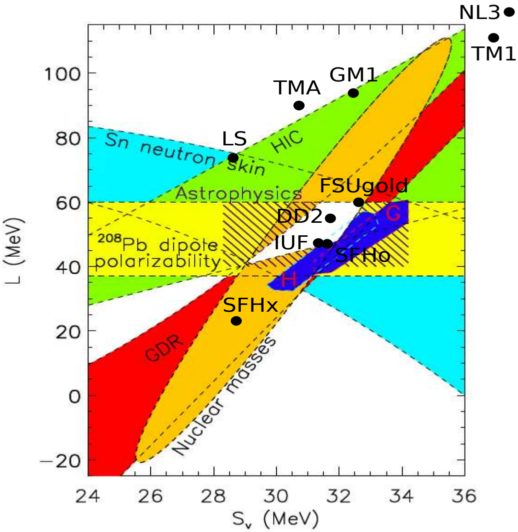
The free energy density is defined as

$$f = \sum_{A,Z} f^0_{A,Z}(T,n_{A,Z}) + f_{Coul}(n_e,n_{A,Z}) + \xi f^0_{nuc}(T,n'_n,n'_p) - T\sum_{A,Z} n_{A,Z} \ln\kappa$$

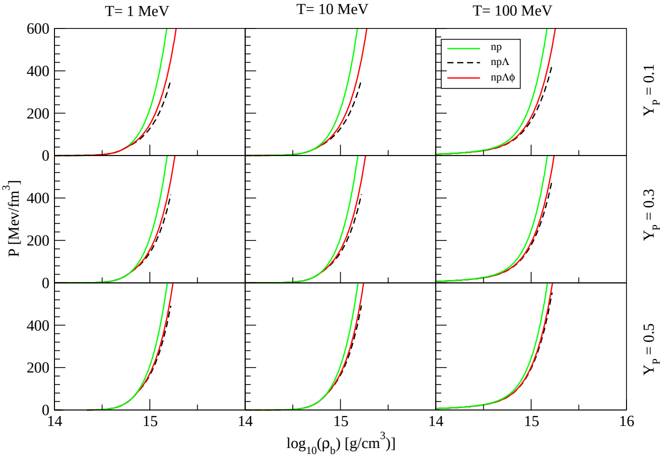
where the last term goes to infinity when available volume fraction of nuclei (κ) is zero near saturation density.

For the merging of the two tables, we follow

i) the free energy per baryon at fixed T, n_B, and Y_p has to be minimized, ii) hyperon fraction is small i.e. 10^{-5}.



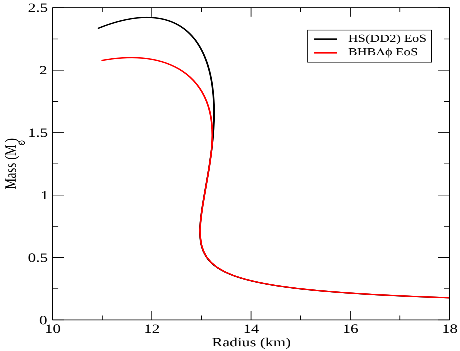
J. M. Lattimer and Y. Lim, ApJ 771, 51 (2013)



S. Banik, M. Hempel, D.B. , ApJS214 (2014) 22

Mass-Radius Relation of Neutron Stars

Hyperon EoS is compatible with a 2 $M_\odot$ Neutron Star. S. Banik, M. Hempel, D.B., ApJS214



SN Simulations in GR1D

The line element in General Relativistic 1D Model called GR1D is described below [Ref:C. D. Ott and E. O'Connor, Class.Quant.Grav.27 114103, 2010],

$$ds^2 = -\alpha(r,t)^2 dt^2 + X(r,t)^2 dr^2 + r^2 d\Omega^2 \ ,$$

where $\alpha(r,t) = exp^{(\Phi(r,t))}$ & $X(r,t) = [1 - 2m(r)/r]^{-1/2}$.
The fluid stress-energy tensor & matter current density are

$$T^{\mu\nu} = \rho h u^\mu u^\nu + g^{\mu\nu} P$$

$$J^\mu = \rho u^\mu \ .$$

Fluid evolution equations are derived from local conservation laws

$$\nabla_\mu T^{\mu\nu} = 0$$

;

$$\nabla_\mu J^\mu = 0$$

ν reactions with matter in supernova core

ν number, energy change → heating/cooling of matter

- Weak interaction, difficult experiments
- Dependence on energy (E_ν), nuclei (A, Z)

→ We need the information of composition

- Emission/absorption:

$e^- + p \leftrightarrow \nu_e + n$ $\qquad$ $e^- + A \leftrightarrow \nu_e + A'$

$e^+ + n \leftrightarrow \bar{\nu}_e + p$

- Scattering:

$\nu_i + N \leftrightarrow \nu_i + N$ $\qquad$ $\nu_i + A \leftrightarrow \nu_i + A$

$\nu_i + e \leftrightarrow \nu_i + e$

- Pair creation/annhilation:

$e^- + e^+ \leftrightarrow \nu_i + \bar{\nu}_i$ $\qquad$ $\gamma^* \leftrightarrow \nu_i + \bar{\nu}_i$

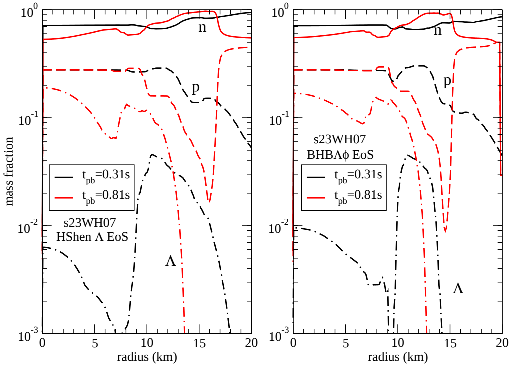
$N + N \leftrightarrow N + N + \nu_i + \bar{\nu}_i$ $\qquad$ $i = e, \mu, \tau$

- A computationally more effecient scheme for neutrinos is chosen over the Boltzmann transport for example, in GR1D [ApJ730,2011].
- Neutrino emission takes place after electron-capture by free or bound protons leading to fall of Y_e at the core.
- Prebounce: effective $Y_e(\rho)$ approximation [Ref: Liebendörfer, Astrophys.J. 633 (2005)].
- Postbounce: 3-flavor, energy-averaged neutrino leakage scheme, which captures the effects of cooling.
- The leakage scheme provides approximate energy and number emission rates [Ref: Ruppert et al., A & A 311, 1996; Rosswog & Liebendörfer, MNRAS 342, 2003].
- Neutrino heating is included via a parameterized charged-current heating scheme. [Ref:H. T. Janka, A & A, **368**, 527 (2001)].

$$\nu_e + n \longrightarrow e^- + p$$
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

For a set of progenitor models of Wooseley and Heger, [Ref: S. E. Woosley and A. Heger, Phys. Rep. **442**, 269 (2007)] we show simulation results using GR1D and BHB$\Lambda\phi$ and Shen Λ hyperon EoS.

Supernova Simulations with New Hyperon EoS



P. Char, S. Banik, D.B., submitted to ApJ

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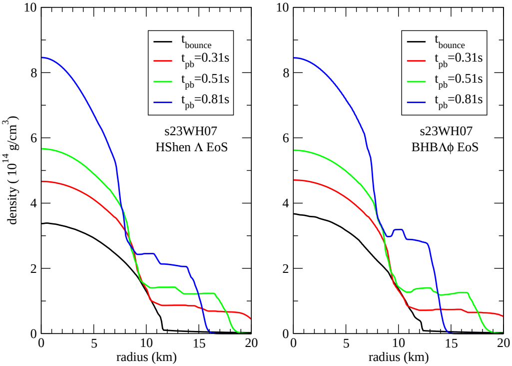

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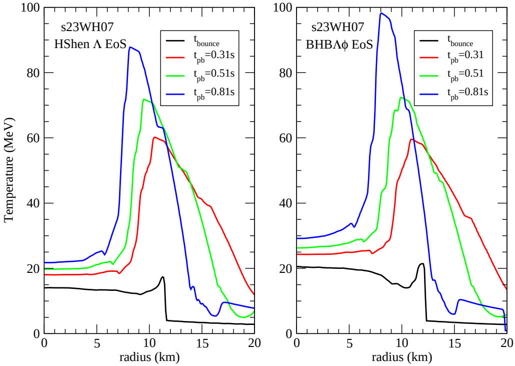

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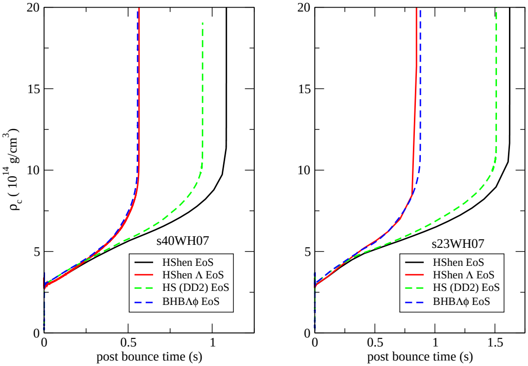
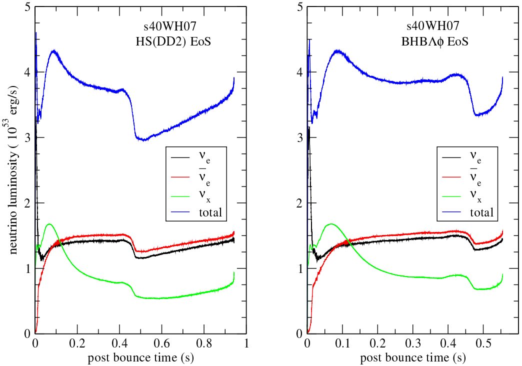


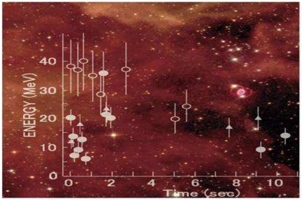
P. Char, S. Banik, D.B., submitted to ApJ

Neutrinos as probe of hyperon matter



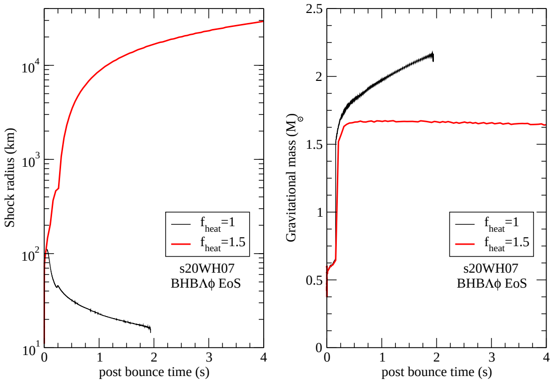
P. Char, S. Banik, D.B., submitted to ApJ

Supernova 1987A



- Occurred in Large Magellanic Cloud
- Mass of Progenitor Star $\sim 18 M_{\odot}$
- Distance from the earth 1,60,000 light years
- Neutrino-antineutrino pairs were created from the heat energy and radiated away
- In Kamiokande, Japan, antineutrinos were detected through $\bar{\nu}_e + p \rightarrow e^+ + n$
- But where is the neutron star? Exotic Matter!

Long Duration Supernova Simulations



P. Char, S. Banik, D.B., submitted to ApJ

Summary and Outlook

- New Hyperon EoS is compatible with density dependence of the symmetry energy and 2 $M_\odot$ neutron star.
- Hyperon EoS fails to generate a second neutrino burst and shock.
- The hadron-hyperon phase transition is a weak phase transition.
- Hyperon emergence in the collapse produces an intense but short neutrino burst, that may be used as a probe of exotic matter.

Collaborators

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