Quark-hadron phase transition and the effects on the structures of compact stars

Nobutoshi Yasutake
(NAOJ; National Astronomical Observatory of Japan)

collaborators
Toshiki Maruyama (JAEA), Toshitaka Tatsumi(Kyoto Univ.)
1. Introduction & background
2. Pasta structures of quark-hadron phase transition at finite temperature
   (NY, M. Maruyama and T. Tatsumi, 2009b, PRD)
3. The implications to astrophysical phenomena
cf.
   - Effects of chiral restoration on EOSs
     (NY, and K.Kashiwa, 2009a PRD)
   - Thermal Evolution of magnetized rotating compact stars
     (NY, K.Kotake, and K.Kiuchi, 2010 in prep.)
4. Summary
Section 1: Introduction and background
Nuclear Force 2009-2010

“Experiment”
J-PARC starts to operate in 2009
J-RARC

“Numerical experiment”
Lattice QCD

Full QCD ($m_\pi = 701$ MeV, $a = 0.09$ fm, $L = 2.9$)
using PACS-CS configuration

Ishii, Aoki & Hatsuda (2009)

Nemura, Ishii, Aoki & Hatsuda (2009)
YN, YY interactions

- How to decide them?
  “two body scattering experimental data of two particles”
  - NN scattering data ~ 4000
  - YN ~ 40 → many ambiguities
  - YY = 0 → unknown

- How to use them for EOSs “directly”?
  - variational principle method
  - Brueckner Hartree Fock model
“Two body NN interaction from variational principle”

Problems
1. No YN, YY interaction now.
2. Causality is broken at high density.

H. Kanzawa et al.,

APR Fermi Hypernetted Chain Calculation
Brueckner Hartree Fock model
Baldo, Schulze (Catania univ.), Takatsuka (Iwate univ.) etc.

We get energy (EOSs) from nuclear force potential self-consistently.

With YN interaction $\rightarrow$ EOSs become TOO SOFT!!

To solve this problem,
1. Three body force
2. Relativistic effects (DBHF: Lattimer et al.)
3. Quark-hadron phase transition
   (Baldo, Burgio et al. Maruyama et al.)

\[ \varepsilon_H = \sum_{i=n,p,\Lambda,\Sigma} \sum_{k<k_f} \left[ T_i(k) + \frac{1}{2} U_i(k) \right]. \]

\[ U_i^{(j)}(k) = \sum_{k'<k_f^{(j)}} \Re \langle k'k'|G_{(ij)(ij)}[E_{(ij)}(k, k')]|kk' \rangle. \]

\[ G_{ab}[W] = V_{ab} + \sum_c \sum_{p,p'} V_{ac} \langle pp'|G_{cb}[W]\langle pp'|. \]

\[ U_i(k) = \sum_{j=n,p,\Lambda,\Sigma} U_i^{(j)}(k) \]

\[ M/M_\odot \]

\[ R [\text{km}] \]
Hadron-Quark phase transition in proto-neutron stars

NY and Kashiwa (2009)

Hadron matter: Shen et al. 1998 (RMF theory)

+ Quark matter: Nambu=Jona-Lasinio model (Chiral symmetric restoration)

The difference comes from the uncertainty of “Finite size effects”.

bulk Gibbs construction (zero surface tension limit)

Maxwell condition (infinite surface tension limit)
Non-uniform structures on the first order phase transition in multi-components systems; “Nuclear Pasta”
G.Watanebe, T.Maruyama, etc.

- **droplet**: $0.100\rho_0$
- **rod**: $0.200\rho_0$
- **slab**: $0.393\rho_0$
- **tube**: $0.49\rho_0$
- **bubble**: $0.57\rho_0$

Red: proton
Green: neutron

$\rho_0 = 0.168 \text{ fm}^{-3}$
**nucleon pasta** ➔
Small effect on structures of compact stars.

**quark-hadron pasta**
Mass-radius relations change drastically.

From Weber’s HP
Section 2:
Pasta structures of quark-hadron phase transition at finite temperature
Non-uniform structure on the Hadron-Quark phase transition
NY, T.Maruyama, and T.Tatsumi (PRD 2009 b)

We do not use QMD, since it is not appropriate to express HQ phase transition.

Hadron: Brueckner Hartree Fock with hyperons (Baldo et al. 1999)
including NN, NY interactions
→ We will update them from the results of lattice QCD or J-PARC.

+ Quark: MIT bag model
→ Nambu=Jona-Lasinio model, etc… (Blaschike …)

Pasta structure needs
・ charge neutrality
・ chemical equilibrium →
・ baryon number conservation
・ balance between “surface tension” and “Coulomb interaction”
Finite temperature technique

Hadron: “Frozen Correlations Approximation”

Quark:

Total Energy

Free Energy
Result ①; EOS

1: EOS gets close to the one under the Maxwell condition.
   ➔ Mixed phase becomes unstable at finite temperature.

2: At some density region, EOS becomes softer than the one at zero temperature.
   ➔ The degree of freedom for QM is larger than HM.
   ➔ F/A of QM becomes lower than the one of HM.
   ➔ QM is favored at finite temperature.
Result ②; Stability of pasta structures

Stability curve

Components of F/A

\[ T_c \sim 60 \text{ MeV} \]

thick curve; \( T=50 \text{ MeV} \)
thin curve; \( T=0 \text{ MeV} \)

The main component in the change of F/A is “the correlation energy”. 
Result ③; Suppress of hyperons by non-uniform structures
Section 3:
The implications to astrophysical phenomena
Our next steps

Chiral symmetry restoration?

Magnetic field in NSs. \( \rightarrow \) the effects?

Gravitational wave from NS-NS binaries?

3D pasta?

Cf. NY and Kashiwa (2009 a) PRD
+ NY, Maruyama, Tatsumi, (2009 b) PRD

Cf. NY, Kiuchi, Kotake (2010 a) MNRAS
NY, Kotake, Kiuchi, 2010 in prep.

Cf. M. Shibata Group

Effects of chiral symmetry restoration on EOSs

NY and Kashiwa (2009 a) PRD

High Yl → High Ye → low $n_s$
→ The chiral symmetry restoration of s-quark is suppressed.
→ Hard EOS !!

High Yl → High Ye → low $n_n$
→ The repulsive nuclear force is suppressed.
→ Soft EOS !!
M-$n_{BC}$ relations

Hadron
(Shen et al.1998)

<Without the phase transition>

Ejection of neutrinos

$\rightarrow$ The EOS becomes HARD !!

<With the phase transition>

Ejection of neutrinos

$\rightarrow$ The EOSs become SOFT !!
Our next steps

Chiral symmetry restoration?

Magnetic field in NSs. → the effects?

Gravitational wave from NS-NS binaries?

3D pasta?

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Cf. NY and Kashiwa (2009 a) PRD
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Magnetic field of compact stars

NY et al. 2010 in prep. (Tomimura & Erigushi method)

EOS: Sly EOS, core density = 1d15 g/cc

We will treat rotating magnetic stars under the following assumptions. (1) The stars are in stationary states. (2) The density distributions and the magnetic field distributions are axisymmetric about the same axis. (3) The sources of the magnetic fields, i.e. the current distributions, are confined only within the stars. (4) The conductivity of the gas is assumed to be infinite. (5) As for the gas, we adopt the barotropic equation of state as follows:
# Thermal evolution of magnetized rotating compact stars (2D simulation)

<table>
<thead>
<tr>
<th></th>
<th>evolution</th>
<th>Initial condition</th>
<th>heating</th>
<th>thermal conductivity</th>
<th>EOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auguilera et al. 2008 (Pons et al.)</td>
<td>2D Full Isothermal</td>
<td>TOV + 2D Force Free B</td>
<td>Joule heating</td>
<td>Effects of magnetic field</td>
<td>Nucleon</td>
</tr>
<tr>
<td>Page et al. 2006 (Geppert et al.)</td>
<td>1D full evolution</td>
<td>TOV + 2D Force Free B</td>
<td>---------</td>
<td>Effects of magnetic field</td>
<td>Nucleon</td>
</tr>
<tr>
<td>Xiaoping et al. 2008 (Kang et al.)</td>
<td>1D Isothermal</td>
<td>2D perturbative hydro static</td>
<td>Latent heat</td>
<td>---------</td>
<td>Quark+ Nucleon</td>
</tr>
<tr>
<td>Our 1st step</td>
<td>1D Isothermal</td>
<td>2D full hydro static</td>
<td>Joule heating</td>
<td>---------</td>
<td>Nucleon</td>
</tr>
</tbody>
</table>
Our Preliminary Results

standard cooling with joule heating

\[ \text{rhomax} = 5 \times 10^{14} \, [\text{g/cm}^3] \]

\[ \begin{align*}
\text{B}_p &= 3.8 \times 10^{15} \, [\text{G}] \\
\text{B}_{\text{max}} &= 1.5 \times 10^{16} \, [\text{G}] \\
\end{align*} \]

\[ \begin{align*}
\text{B}_p &= 1.9 \times 10^{15} \, [\text{G}] \\
\text{B}_{\text{max}} &= 7.3 \times 10^{15} \, [\text{G}] \\
\end{align*} \]

\[ \begin{align*}
\text{B}_p &= 3.8 \times 10^{14} \, [\text{G}] \\
\text{B}_{\text{max}} &= 1.5 \times 10^{15} \, [\text{G}] \\
\end{align*} \]

\[ \begin{align*}
\text{B}_p &= 7.1 \times 10^{15} \, [\text{G}] \\
\text{B}_{\text{max}} &= 2.7 \times 10^{16} \, [\text{G}] \\
\end{align*} \]

\[ \begin{align*}
\text{B}_p &= 3.5 \times 10^{15} \, [\text{G}] \\
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\text{B}_p &= 7.1 \times 10^{14} \, [\text{G}] \\
\text{B}_{\text{max}} &= 2.7 \times 10^{15} \, [\text{G}] \\
\end{align*} \]

\[ \begin{align*}
\text{rhomax} &= 1 \times 10^{15} \, [\text{g/cm}^3] \\
\end{align*} \]
Section 4: Summary
We have studied the hadron-quark mixed phase at finite temperature.

At finite temperature,
1. EOS gets close to the one under the Maxwell condition.
2. At some density region, EOS becomes softer than the one at zero temperature.
   etc.

These behaviors will affect astrophysical phenomena such as NS-NS mergers, cooling of compact stars.
1. Super Strong magnetic field will change EOSs and structures of NSs. → Some “knots” appear by Landau level effects. → GW will change.

Our results of RMF EOSs with super strong magnetic filed(4d18 G).

2. Paring effects, such as CFL or super-conductivity of nucleons, will change cooling light curves. (Reddy, Schulze ...)

3. Other exotic EOSs will also change the cooling process, structures of NSs, the magnetic filed, and the heating effects.

4. Thermal conductivities with magnetic field are different from the ones without magnetic field.