Probing Quark Matter in Neutron Stars

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• Quark matter in neutron star interiors may have distinctive signatures in basic observables such as

(1) masses and radii,

(2) surface temperatures versus spin-down age,

(3) spin-down rates of milli-second pulsars, and

(4) $\nu$—luminosities from core collapse supernovae.

• What are the prospects of detecting quarks through observations

  $\rightarrow$ in X-ray, UV, optical, and radio frequencies with the HST, Chandra, XMM etc., and,

  $\rightarrow$ of supernova neutrinos from detectors such as the SuperK, SNO, and others including UNO?

• Gains: Delineation of QCD at finite baryon density in addition to the composition, structure, and evolution of both newly-born and old neutron stars.
The diagram illustrates the stages of a presupernova event, focusing on the processes occurring in the core of a massive star.

**Stage 1**
- Initial conditions: $R \sim 200 \text{ km}$, $0 < s < 10$, $0 < Y_i < 0.4$, $M_c \sim 0.7 M_\odot$, $r \sim 20 \text{ km}$, $s \sim 1$, $Y_L \sim 0.4$.
- Processes: Shock, standoff shock.

**Stage 2**
- Conditions: $R \sim 20 \text{ km}$, $1 < s < 3$, $Y_L \sim 0.4$.
- Processes: Accretion, shock lift-off, mantle collapse.
- Time: $t \sim 0.5 - 1 \text{ s}$.

**Stage 3**
- Conditions: $R \sim 15 \text{ km}$, $s = 2$, $Y_v = 0$.
- Processes: Deleptonization, core heating.
- Time: $t \sim 15 \text{ s}$.
- Description: Maximum heating, appearance of quarks, hyperons.

**Stage 4**
- Conditions: $R \sim 12 \text{ km}$, $s = 0$, $Y_v = 0$.
- Processes: Core cooling, $\nu$ cooling.
- Time: $t \sim 50 \text{ s}$.
- Description: $\nu$-transparency, cold core, warm crust.

**Stage 5**
- Conditions: $R \sim 12 \text{ km}$, $s = 0$, $Y_v = 0$.
- Processes: Cooling.
- Time: $t \sim 50 - 100 \text{ yr}$.
- Description: Star becomes isothermal.

**Stage 6**
- Conditions: $R \sim 12 \text{ km}$, $s = 0$, $Y_v = 0$.
- Processes: Standard core cooling, modified Urca.
- Time: $10^2 \text{ yr} < t < 3 \times 10^6 \text{ yr}$.
- Description: Observable as X-ray thermal emission.
(1) $t=0\text{ s}$ standoff shock

$R \sim 200\text{ km}$
$5 \leq s < 10$
$0 < Y_e < 0.4$

$M_z \sim 0.7\ M_\odot$
$r \sim 20\text{ km}$
$s \sim 1$
$Y_\nu \sim 0.4$

(2) $t \sim 0.5-1\text{ s}$
occultation shock lift-off
mantle collapse

$R \sim 20\text{ km}$
$1 \leq s < 3$
$0 < Y_e < 0.4$

(3) $t \sim 15\text{ s}$
maximum heating

(4) $t \sim 50\text{ s}$

$R \sim 12\text{ km}$
$s = 0$
$Y_e = 0$

$\nu$ core cooling

$\nu$-transparency
cold core, warm crust

(5) $t \sim 50-100\text{ yr}$

$R \sim 12\text{ km}$
$s = 0$
$Y_e = 0$

$\nu$ cooling

$\nu$ cooling

(6) $10^2 < t < 3 \times 10^6\text{ yr}$

observable as X-ray thermal emission

$T_s \sim 3 \times 10^5\text{ K}$

$R \sim 12\text{ km}$
$s = 0$
$Y_e = 0$

rapid core cooling
(Urca)

$T_s \sim 10^6\text{ K}$

$\gamma$ cooling

standard core cooling
(modified Urca)
The Basic Equations

Structure:
(TOV)

\[
\frac{\partial P}{\partial r} = - (\rho + P) \frac{e^{2\Lambda}}{r^2} (m + 4\pi r^3 P) \\
\frac{\partial \mu}{\partial r} = 4\pi r^2 n_B e^\Lambda \\
\frac{\partial m}{\partial r} = 4\pi r^2 \rho
\]

Transport:

\[
\frac{dY_\nu}{d\tau} + e^{-\phi} \frac{\partial(e^\phi 4\pi r^2 F_\nu)}{\partial \mu} = \frac{S_N}{n_B} \\
\frac{dY_e}{d\tau} = - \frac{S_N}{n_B}
\]

\[
\frac{dE}{d\tau} + P \frac{d(\frac{1}{n_B})}{d\tau} + e^{-2\phi} \frac{\partial(e^{2\phi} 4\pi r^2 H_\nu)}{\partial \mu} = 0
\]

metric:

\[
ds^2 = - e^{2\phi} dt^2 + e^{2\Lambda} dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2
\]

\[
e^{\phi} = \sqrt{-g_{00}} \quad e^{2\Lambda} = \frac{1}{(1 - 2Gm/rc^2)} \quad \frac{d}{d\tau} = e^{-\phi} \frac{d}{dt}
\]

\[
n_B := \text{baryon density} \quad \mu := \text{enclosed rest mass} \\
m := \text{enclosed mass} \quad \rho := \text{mass-energy density} \\
F_\nu := \text{Lepton Flux} \quad H_\nu := \text{Energy Flux} \\
S := \text{source term} \quad \tau := \text{proper time}
\]
Evolution of Protoneutron Stars

- Physical Inputs (Dense Matter EOS & $\nu$—Opacities)
  1. Stiffness of nucleonic EOS
  2. Effects of composition (strangeness) & phase transitions
  3. $\nu$—opacities consistent with the EOS

- Neutrino Transport (Diffusion Approximation)
  1. Allows comparision to earlier works
  2. Connections between microphysical ingredients & global characteristics of $\nu$—emission
  3. Multigroup approach required for precise $\nu$—spectra

- Neutrino Signals (Sensitivity)
  1. Baseline simulations
  2. Vary initial conditions & remnant mass
  3. Vary composition and physical state of matter
  4. Metastable neutron stars

  - remnant mass, composition & EOS of dense matter
  - $\nu$—mass, magnetic moment, $\times$ oscillations, ...
  - ....
NEUTRINO TRAPPED STARS
(Newborn neutron stars)

- Entropy/baryon $\sim 1 - 2$

- Leptons/baryons $Y_{\ell\ell} = Y_{\ell} + Y_{\nu\ell}$, ($\ell = e, \mu$ and $\tau$) conserved on dynamical timescales of collapse

- Neutrinos trapped!

- Chemical equilibrium

$$\Rightarrow \mu_i = b_i \mu_n - q_i (\mu_{\ell} - \mu_{\nu\ell})$$

$b_i$: baryon #
$q_i$: baryon charge
$\mu_{\nu\ell}$: neutrino chemical potential

- Collapse calculations

$$\Rightarrow Y_{Le} = Y_e + Y_{\nu e} \simeq 0.4$$
$$Y_{L\mu} = Y_\mu + Y_{\nu\mu} \simeq 0.0$$
Phase Diagram

\[ n_B (\text{fm}^{-3}) \]

\[ n_e \]

\[ Y_{\nu_e} \]

\[ B = 200 \text{ MeV/fm}^{-3} \]

MS-NJL

npHQ

MS-MIT

npQ

\[ n_e \]
- Neutrino trapping creates metastable configurations in all models - The maximum mass decreases upon deleptonization
\[ Y_{\nu e} = \frac{n_{\nu e}}{n_b} \]
Temperature decreases along an adiabat as a function of density in the mixed phase.

This may have an observable effect on neutrino spectra - Lower temperature tends to decrease the neutrino energies and increase the neutrino mean free paths.
Figure 3: $\nu_e$ cross sections with various particles as a function of baryon density ($n_0 = 0.16$ fm$^{-3}$) in the mixed phase. The upper panels correspond to Stage 2 in Fig. 1 and the lower panels correspond to Stage 3. Thick lines show the mixed phase region. Color designation: hadrons-red, quarks-green, leptons-blue, and total-black.
Fig. 10.—
CONCLUSIONS

1. Appearance of hyperons, bosons and/or quarks is delayed to higher density in neutrino-trapped (lepton-rich) matter

2. Nascent neutron stars, with negatively charged strongly interacting particles, have larger maximum masses than their cold catalyzed counterparts; a reversal in behavior from matter containing only neutrons, protons and leptons

3. Above permits existence of metastable young stars that could collapse to black holes during deleptonization

4. In all cases, effects of entropy (of order 1 or 2) on the maximum mass are small in comparison to effects of neutrino trapping
\[ \mu_q = 400 \text{ MeV}, \ \Delta_0 = 100 \text{ MeV} \]

- Black solid line: \( \frac{\tau_c}{\tau_c} \)
- Green dashed line: \( \frac{\lambda_s}{\lambda_s} \)
- Blue dashed line: \( \frac{\Delta(T)}{\Delta_0} \)
- Red dash-dotted line: \( \frac{C_v^\Delta}{C_v} \)
Tasks for Better Predictions

→ Treat semi-transparent regions using multi-group neutrino transport to determine \( < E_\nu >_i, (dN/dE_\nu)_i \) & \( (dN/dt)_i \).

→ Couple convection with neutrino transport as large regions are convectively unstable.

→ Include self-consistent hydrodynamical models with accretion, which adds mass and contributes significantly to \( L_\nu \).

- Simulations with Bose condensates or quarks could provide contrasts with hyperons, since feedbacks involving the specific heat and \( \nu \)-opacities are different.

Note:

→ Crucial for early time signals

- Relevant for late time signals
CONCLUSIONS

- From observations of neutron star cooling,
  → one could constrain the smaller of the $n-$ or $\Lambda-$ pairing gaps and the star's mass;
  → deducing the sizes of quark gaps will be difficult;
  → large $q-$gaps render quarks invisible; &
  → vanishing $q-$gaps lead to cooling behaviors which are indistinguishable from those of $np$ or $npH$ stars.

HOWEVER,

Think This Titillating Thought!

- The observation of a neutron star
  older than $10^6$ y & hotter than $\sim 10^7$ °K
  signals quarks with large gaps in neutron stars!!