The Astrophysics of Strange Matter

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Quark Matter

\( T >> \mu \)
- Quark-gluon plasma phase
- filled the universe after microsecond of big bang
- created in the laboratory in relativistic heavy ion collisions

\( T << \mu \)
- rich variety of symmetry breaking
- might exist in the interior of compact objects like neutron stars
- time enough for weak interaction – strangeness production

Quark Matter and neutron stars

• Different facets:

(a) Symmetry structures at high density systems

(b) Consequences of a quark matter phase for example: gravitational waves GRB connection

(c) Mechanism of the phase transition itself
Symmetries

Alford et al.
hep-ph/0709.4635
Rev. Mod. Phys.
Phase Transition: Consequences

• Cooling
  1. Direct URCA
     Relativistic NM, Unpaired QM, pion and kaon condensates
     single flavour pairing
     \[ n \rightarrow p + e^- + \overline{\nu}_e \quad \varepsilon_v \propto T^6 \]
     \[ d \rightarrow u + e^- + \overline{\nu}_e \quad \varepsilon_v \propto T^8 \]
     \[ n + X \rightarrow p + X + e^- + \overline{\nu}_e \]
     \[ \nu_e \varepsilon \nu_e \propto \exp(-E/T) \]

  2. Modified URCA
     NM at lower density
     (proton fraction < 0.1)

  3. CFL phase
     \[ \pi^\pm, K^\pm \rightarrow e^\pm + \overline{\nu}_e \]
     \[ \pi^0 \rightarrow \nu_e + \overline{\nu}_e \]
     suppressed by \( \exp(-E/T) \)

     \[ \varphi + \varphi \rightarrow \varphi + \nu_e + \overline{\nu}_e \]
     \[ \varepsilon_v \propto T^{15} \]

Gravitational Waves

- Ripples in space-time curvature propagating through space at the speed of light

- because of their compactness, oscillating neutron star could be interesting astrophysical source of gravitational wave

- maybe detected by new generation of gravitational wave detectors
Consequences

- $r$ – Mode instability
  - bulk flow known as Rossby modes or $r$ (rotational) mode
  - coriolis force effect
  - radiates away the energy and angular momentum in form of gravitational wave
  - so above a critical frequency spin slow down
  - critical frequency depends on the sources of damping e.g. shear and bulk viscosity – larger damping implies larger critical frequency
  - strange stars have larger viscosity so will be affected immediately i.e. strange stars may have higher frequency
  - $r$-mode rules out CFL quark stars
  - may provide signature of hybrid stars

Madsen PRL85, Andersson et al. IJMPD10, 381 (2001)
(For boson condensation picture see Chatterjee et al. PRD75 (2007))
Hadron-quark phase transition – GRB connection

What happens in phase transition?

1. Hadronic sector: small no. of strange baryons, small strangeness fraction (strange baryon density/total baryon density)

2. Quark sector: Strangeness fraction \( \sim 1 \)

Ghosh et al. Zphys C1995
\[ \mu = \cos \theta \]
\[ \theta \rightarrow \text{polar angle} \]

Sharp peak - $\mu = 0.1$ and 0.24
\[ \theta \approx 12 \text{ degrees} \]

Ghosh et al. PLB635 (2006)
GRB connection ....

- Time scale $10^{-3} - 10^{-1}$ seconds

\[ \nu + \bar{\nu} \rightarrow e^+ + e^- \]

★ Normally small energy deposition
★ The high gravity environment might enhance the deposition
(Salmonson & Wilson APJ, 517 (1999) 859)

Result of two effects
1. Path bending of neutrinos
2. Gravitational red shift
   ⇒ 10% energy deposit

Effect of rotation and gravitation
Bhattacharyya et al. astro-ph/0707.2475  (see Poster for details)
GRB connection…….

- Magnetized star in CFL phase

  (a) High initial temperature - 30 – 60 MeV

  (b) High surface magnetic field - $10^{15} - 10^{17}$ G

  - collimated neutrino emission
  - time scale 0.001 sec.

Mechanism of phase transition

- **Two step process**
  - (a) hadronic matter to two flavour matter
    - deconfinement
    - $t \sim \text{milliseconds}$
  - (b) two flavour to three flavour matter
    - generation of strange quark via weak process
    - $t \sim 100 \text{ seconds}$

  *Presence of two fronts?*

  *Bhattacharyya et al. PRC74, 065804 (2006)*

- **General relativistic effects**

  *Bhattacharyya et al. PRC76, 052801(R) (2007)*

  (see poster for details)
**Early Universe**

- **Contents of the Universe:**
  5% Atoms, 25% Cold Dark Matter, 70% Dark Energy

**Different Epochs:**

- Planck Scale: $E \sim 10^{19} \text{ GeV}$
- GUT: $E \sim 10^{16} \text{ GeV}$
- Electroweak: $E \sim 100 \text{ GeV}$
- QCD: $E \sim 100 \text{ MeV}$
- Nucleosynthesis: $E \sim 2 \text{ MeV}$
- Recombination: $E \sim 10 \text{ eV}$

**QCD:**

(a) Initial conditions for nucleosynthesis
(b) Relics of transition may observed today
QCD phase transition

1\textsuperscript{st} Order:
- Position of the minimum of free energy jumps discontinuously
- Free energy difference gives latent heat
- Speed of sound is zero in mixed phase
QCD Phase Transition

- Lattice results

- Sharp change in energy density
- Sharp drop in speed of sound

Gupta S. Pramana 61, 877 (2003), S. Raha(1983)
Debye Length and QGP

- colour charges neutralised within Debye length \( d \sim 1/gT \)
- \( d < \text{hadronic radius} \ (R) \) \( \Rightarrow \) no bound state of coloured charges
- life time of QGP \( \equiv \) temperature at which \( d > R \)
- Universe \( >> d \) \( \Rightarrow \) Overall colour neutral
- need for sufficient no. of colour charge inside debye volume
- upto \( T_c \) \( d \sim \) fm, total colour charge inside inside debye volume \( \sim 10 \)
- Baryon number is carried by quarks
- \( \Rightarrow \) net quark no. \(-\) multiple of 3
- Net quark no. within Debye volume \( \sim 10^{-9} \)
  \( \Rightarrow \) Need for long range correlation for colour neutrality and integer baryon number
  \( \Rightarrow \) Quantum Entanglement
Role of colour Charge

Assumption: Many body system
\[\downarrow\]
Colour is averaged
\[\downarrow\]
Only statistical degeneracy

Too Simplified ?????
• Before P.T. ➔ Universe singlet
  ➔ Wave functions of coloured objects entangled
  ➔ Universe characterized by perturbative vacuum
  ➔ During P.T. local colour neutral hadrons
  ➔ Gradual decoherence of entangled wave functions
  ➔ Proportionate reduction of vacuum energy
In Quantum mechanical sense

completion of quark-hadron P.T.

⇓

Complete decoherence of colour wave function

⇓

Entire vacuum energy disappear

⇓

Perturbative vacuum is replaced by non-perturbative one

Does that really happen ?????
Colour neutral

⇒

All have integer baryon number

⇒

At the moment of formation quark number multiples of 3

⇒

Statistical system ➔ some residual colour

⇒

For colour neutrality: one or two residual quarks
End of cosmic quark-hadron phase transition

- few coloured quarks separated in space
  - Colour wave functions are still entangled
    - Incomplete decoherence
      - Residual perturbative vacuum energy
Dark Energy $\sim 10^{-48}$ GeV$^4$ ($\Omega_{DE} \sim 0.7$)

- DE $\Rightarrow$ Constant

- Matter density $\Rightarrow$ decreases as $R^{-3}$

**DE is dominant at late times**  
*Banerjee et al. PLB611 (2005)*

*Another Picture: Oaknin et al. PRD71(2005)*

CS matter nugget – antinugget separation of charges

Baryogenesis after QCD Phase transition
Summary

• High density physics has interesting possibilities

• Early universe may still be an interesting place in this crossover era
The End