Possibility of conversion of neutron star to quark star with strong magnetic field

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Motivations

• Witten explored the possibility of existence of strange quark matter which is stable in bulk.

• The central pressure and density of a NS may be high enough for a phase transition from hadronic matter to deconfined quark matter to occur.

• If a stable strange matter seed is formed inside a NS, the star will be converted to a SS.

• Because of the high energy conditions at which this burning is expected to occur, it may be related to observable phenomena.

• We study the conversion process considering the effect of strong magnetic field on the EoS of highly dense matter which is important for magnetars.

• We consider the appearance of hyperons at the core of a NS, and hence the conversion is simply the deconfinement of hyperons into strange matter.
Our Model

Hadronic phase...

• We employ nonlinear Walecka model for nucleon-hyperon matter

Quark phase...

• Quarks interact among themselves via two-body Richardson potential.

• Quark masses are density dependent, restoring chiral symmetry at high density.

Dey et al., PLB 438, 123 (1998)
Matter in Magnetic Field

- In magnetic field the motion of a charged particle is Landau quantized in the plane perpendicular to the direction of magnetic field.

- We assume the direction of magnetic field as the z-direction of the system.

\[ \vec{B} = B \hat{z} \]

- In this choice the kinetic energy of any charged particle is

\[ E_n = \sqrt{p_z^2 + m^2 + 2ne|Q|B}. \]

- For charge neutral particle, kinetic energy is

\[ E_p = \sqrt{p^2 + m^2} \]

\[ \varepsilon_k = \int_0^{p_F} E_p \, d^3 \vec{p} \]

\[ \varepsilon = \sum_{B(q)} \varepsilon_{kB(q)} + \varepsilon_p + \sum_l \varepsilon_{kl} \]

\[ P = \sum_B \mu_B n_B + \sum_l \mu_l n_l - \varepsilon \]
Basic Picture

- We assume that seeding of strange matter has occurred inside a NS.
- Eventually it grows converting the NSM into SSM.
- The conversion process (combustion) occurs at the interface of NSM and SSM which moves outwards – from center to the surface of the star.
- The combustion front propagates leaving behind quark matter.
- Olinto modeled the conversion process as slow combustion.
- In a nonrelativistic framework, Horvath and Benvenuto showed that slow combustion is unstable and the conversion takes place by detonation from purely hydrodynamic consideration.
- We study the conversion process and examine the modes of propagation in presence of magnetic field in special relativistic framework.
- We consider non-rotating spherically symmetric star.
- The conversion front propagates radially, reducing the geometry of the problem to one dimensional one.
\[ \omega_1 v_1^2 \gamma_1^2 + P_1 = \omega_2 v_2^2 \gamma_2^2 + P_2, \]

\[ \omega_1 v_1 \gamma_1^2 = \omega_2 v_2 \gamma_2^2, \]

\[ n_1 v_1 \gamma_1 = n_2 v_2 \gamma_2. \]

1 → Hadronic sector
2 → Quark sector

\[ v_1^2 = \frac{(P_2 - P_1)(\varepsilon_2 + P_1)}{\varepsilon_2 - \varepsilon_1)(\varepsilon_1 + P_2)}, \]

\[ v_2^2 = \frac{(P_2 - P_1)(\varepsilon_1 + P_2)}{\varepsilon_2 - \varepsilon_1)(\varepsilon_2 + P_1)}. \]
\[ B(n_b/n_0) = B_s + B_c \left\{ 1 - e^{-\beta \left( \frac{n_b}{n_0} \right)^\gamma} \right\} \]

\[ B_c = 10^{18} \text{ G} \]

\[ B_s = 10^{15} \text{ G} \]
Number density (fm$^{-3}$)

Matter velocities (in natural units)

- $v_1$, $B=0$
- $v_2$, $B=0$
- $v_1$, $B=1 \times 10^{18}$ G
- $v_2$, $B=1 \times 10^{18}$ G
- $v_1$, $B=3 \times 10^{18}$ G
- $v_2$, $B=3 \times 10^{18}$ G

Number density (fm$^{-3}$)

Matter velocities (in natural units)
Propagation of Shock

\[
\frac{1}{\omega} \left( \frac{\partial \varepsilon}{\partial \tau} + v \frac{\partial \varepsilon}{\partial r} \right) + \frac{1}{W^2} \left( \frac{\partial v}{\partial \tau} + v \frac{\partial v}{\partial r} \right) + 2 \frac{v}{r} = 0
\]

and

\[
\frac{1}{\omega} \left( \frac{\partial P}{\partial \tau} + v \frac{\partial P}{\partial r} \right) + \frac{1}{W^2} \left( \frac{\partial v}{\partial \tau} + v \frac{\partial v}{\partial r} \right) = 0,
\]

\[
\frac{dv}{dr} = \frac{2vkW^2(1 + v^2)}{r [4v^2 - k(1 + v^2)^2]}
\]

Tokareva et al., IJMPD 14, 33 (2005)

\[u\] → velocity of front in restframe of hadronic matter

\[W\] → inverse of the Lorentz factor

\[k\] → square of the sound speed in the matter
Conclusions

- With the EoSs employed we find that the mode of propagation of combustion front depends on the central density of the initial star.

- We find that range of density for which the formation of shock is possible increases in presence of magnetic field.

- However, the velocity of shock propagation decreases in presence of magnetic field.

- We have considered both the phases to be at zero temperature. The possibility however, exists that part of the internal energy can be converted to heat energy, thereby increasing the temperature.

- In the present work, we use the special relativistic formalism, though a general relativistic formalism is necessary to get the true picture.

- We have not considered the effect of magnetic field on hydrodynamic picture which is necessary to take into account.