Nonequilibrium phenomena in high energy nuclear physics and cosmology

Ritam Mallick[1*]
[1]*Department of physics, Bose Institute,
93/1 A.P.C. Road, Kolkata 700 009, INDIA*

Introduction

Despite the progress in the general understanding in high energy physics and cosmology, subject of nonequilibrium phenomena in these areas is not well understood, especially, the nonequilibrium phenomena related to phase transitions (PT). In the present thesis we would study the PT, specially, the hadron-quark PT which might have taken place at the centre of the highly dense compact stars.

It has been conjectured that strange quark matter (SQM), consisting of almost equal numbers of u, d and s quarks, may be the true ground state of strongly interacting matter [1] at high density and/or temperature. Normal nuclear matter under such condition, would be unstable against conversion to two-flavour quark matter and would eventually decay to SQM in a weak interaction time scale, releasing a finite amount of energy in the process. Such a two step conversion process may take place in the interior of a neutron star (NS) where the densities can be as high as (8-10) nuclear matter saturation density. Therefore NSs may then convert to a strange star (SS) (or a hybrid star (HS)) with a significant fraction of strange quarks in it. Hadron to quark phase transition inside a compact star may also yield observable signatures in the form of Quasi-Periodic Oscillations (QPO) and the Gamma ray bursts (GRB). In this thesis we shall go into the detail of this phase transition, the conversion process and its possible signatures.

*Electronic address: `ritam@bosemain.boseinst.ac.in`

Conversion of NS to SS/HS

We model the conversion of nuclear matter to SQM in a neutron star as occurring through a two step process. Deconfinement of nuclear matter to a two (up and down) flavour quark matter takes place in the first step. The nuclear matter EOS has been evaluated using the nonlinear Walecka model [2]. The final composition of the quark matter is determined from the nuclear matter EOS enforcing the baryon number conservation during the conversion process. Starting from a point, infinitesimally close to the center, hydrodynamic equations are solved radially outward. The velocity of the front shoots up very near to the core and then saturates at a value close to 1 (fig 1.). The time required for this conversion is of the order of few milliseconds. The second front converts the two flavour matter to three-flavour matter via weak interaction processes. As the front moves out from the core to the crust, its velocity increases, implying faster conversion. The time for the second conversion to take place comes out to be ~ 100 seconds.

As NS is a massive rotating object the general relativistic (GR) effect cannot be neglected. The metric describing the structure of the star is given by [3]

$$ds^2 = -e^{\gamma+\rho}dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{\gamma-\rho}r^2 sin^2\theta(d\phi - \omega dt)^2 \quad (1)$$

where α, γ, ρ, ω are the gravitational potentials. Due to the GR and rotational effect the front is not longer continious, it breaks up and propagates with different velocity along different directions.

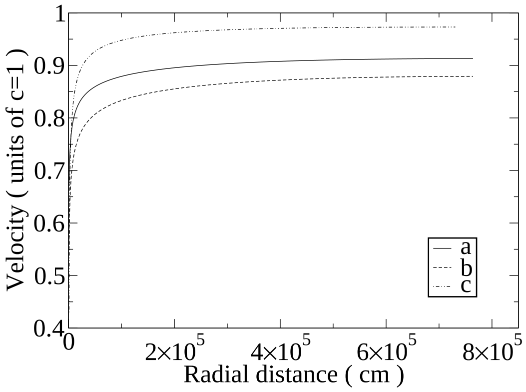

FIG. 1: Variation of velocity of the conversion front with radius of the star for three different values of the central densities, namely, (a) $4.5\rho_0$, (b) $3\rho_0$ and (c) $7\rho_0$, respectively. Here ρ_0 is the nuclear saturation density.

As NSs are found to have very high magnetic fields at surface, we assume a dipole placed at the center of the star oriented along the polar direction. For a field of few times $10^{10}G$ the velocity of the front first dips and then picks up (fig 2.). The 'braking effect' is due to the additional pressure of the magnetic field. For a much higher magnetic field the velocity of the front keeps on decreasing, never picks up, and becomes almost zero *i.e.* the front gets stalled at some distance from the center of the star.

GRB: are they the signatures of such transitions?

In the present model it has been suggested that the origin of the GRBs may be associated with the deconfinement transition inside a neutron star resulting into a HS or a pure QS. The production of huge amount of high energy neutrino-antineutrino pairs during the transition may be the underlying feature of GRBs. These pairs may give rise to electron-positron pairs which may further annihilate to produce gamma rays.

We have done a through GR calculation of the neutrino path inside a rotating star, and have obtained geodesic equation for a neutrino and also calculated the minimum photosphere radius (MPR). We then have calculated the GR effect on the energy deposition rate (EDR) of $\nu\bar{\nu} \rightarrow e^+e^-$ reaction. We have calculated the EDR for the neutrinos coming out of the equatorial disk and depositing energy along the rotation axis of the star, above the equatorial plane and it is few percent of the GRB energy. Most of the energy is deposited near the surface of the star and decreases with distance.

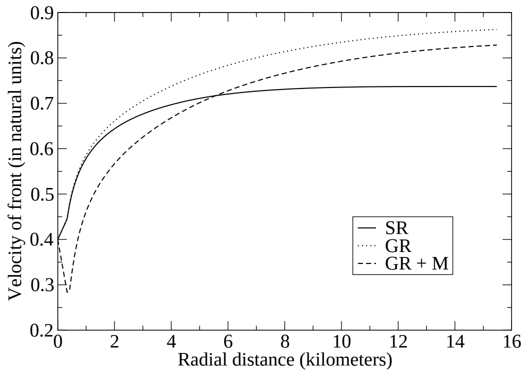

FIG. 2: Variation of velocity of the conversion for three different cases, namely SR, GR and GR+M.

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