

Cosmic Separation of Phases: the microsecond universe and the neutron star.

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Abstract

It is entirely plausible under reasonable condition, that a first order QCD phase transition occurred from quarks to hadrons when the universe was about a microsecond old. Relics, if there be any, after the quark hadron phase transition are the most deciding signatures of the phase transition. It is shown in this paper that the quark nuggets, possible relics of first order QCD phase transitions with baryon number larger than 10^{43} will survive the entire history of the universe upto now and can be considered as candidates for the cold dark matter. The spin down core of the neutron star on the high density low temperature end of the phase diagram initiates transition from hadrons to quarks. As the star spins down, the size of the core goes on increasing. Recently discovered massive Pulsar PSR J 1614-2230 with a mass of $1.97 \pm 0.04 M_{\odot}$ most likely has a strongly interacting quark core. What possible observables can there be from these neutron stars?

Keywords: early universe, RHIC, LHC, quark nuggets, neutron star.

1. Introduction

It is by now conventional wisdom, that collisions between two nuclei at relativistic energies such as at RHIC as well as LHC, lead to the formation of quark gluon plasma (QGP). A large number of novel and exciting discoveries have been made [1, 2]. One of the most surprising observation[3] is to do with the discovery that QGP formed at RHIC and now at LHC does not behave as a non interacting gas of quarks and gluons, as anticipated theoretically but as a "perfect fluid" of very small value of shear viscosity to its entropy density. The deep implication of this recent observation in the cosmological arena of microsecond old universe and the neutron star will be discussed.

Since the chemical potential of the universe, at that primordial epoch was close to zero and the temperature was around 150 MeV [4, 5], the wisdom of lattice will lead the universe to crossover from the universe of quarks and gluons to a universe of hadrons, erasing all the memories, with no relic of the earlier phase of quarks and gluons. It should be noted at this point that the lattice calculation, which is static, is hardly applicable to an expanding universe at a non zero temperature and radiation dominated with bare quark masses.

Sometime ago Witten [6] argued for a first order phase transition with "small" supercooling which means that the transition effectively occurs at a temperature at which most of the latent heat between QGP and hadrons still remains, so that the phase co-existence can be established after nucleation.

More recently Boeckel and Schaffner-Bielich [7] by introducing "little inflation" scenario at the point of quark hadron phase transition have demonstrated that the universe goes through

a first order phase transition without contradicting any contemporary cosmological observation.

2. The Microsecond Universe

At this point it is highly instructive to recapitulate the raison d'être of little inflation and its relevance to that primordial epoch of quark hadron phase transition.

It is to do with baryogenesis. One of the more compelling scenarios of baryogenesis is based on its generation from leptogenesis through topological sphaleron transitions occurring around the electroweak transition temperature. Leptogenesis, in its turn, appears through out-of-equilibrium decays of heavy right-handed neutrinos which occur naturally via a *seesaw* mechanism leading to Majorana masses for neutrinos (as well as neutrino oscillation parameters) within observable ranges. It is supposedly Majorana nature of neutrinos which lies at the heart of the incipient lepton number violation. If, on the otherhand, neutrinoless double beta decay experiments yield null results, and neutrinos are confirmed to be Dirac fermions, the scenario of baryogenesis loses its prime attraction, entailing unsavoury fine tuning.

Given such volatile situation, alternative scenarios of baryogenesis can not be ruled out. Prominent among these is the non-thermal Affleck-Dine [8] mechanism based upon out-of-equilibrium decays of heavy quarks and leptons (which respectively carry baryon and lepton number) within a super symmetric framework. When supersymmetry is unbroken, the scalar potential for quarks and leptons has flat directions which permit these scalars to acquire very large vacuum value.

The Affleck-Dine mechanism has the potential to produce a baryon asymmetry of $O(1)$ without requiring superhigh temperatures. However, the observed baryon asymmetry of $O(10^{-10})$

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at CMB temperatures needs to emerge naturally from such a scenario. This is what is achieved through a 'little inflation' of about 7 e-foldings occurring at a lower temperature which may be identified with the QCD phase transition thought of as a first order phase transition. The universe is thus assumed to begin with a large baryon chemical potential acquired through an Affleck-Dine type of mechanism and then undergoes a period of inflation after crossing the first order QCD phase transition line, while remaining in a deconfined and in a chirally symmetric phase. The delayed phase transition then releases the latent heat and produces concomitantly a large entropy density which reduces the baryon asymmetry to currently observed values. It then enters a reheating phase all the way up to the usual reheating temperature with no significant change in the baryon potential and then follows the standard path to lower temperature.

The universe is then trapped in a false metastable QCD vacuum state. A delayed phase transition takes place. The latent heat thus released caused a large entropy release, diluting the baryon asymmetry to the presently observed value. The microsecond old universe goes from the universe of quarks to universe of hadrons in a first order phase transition. The question one naturally goes on to ask " what possible relic(s) of that primordial epoch can we observe today?"

It is clear however that existence of relics, (say) in the form of Quark Nuggets is a definitive signature of a first order phase transition. Thus one such relics are conclusively discovered, all debates should converge.

Witten pointed out in that seminal paper [6] that consequent to the first order phase transition stable "quark nuggets (QN)" made of "strange quark matter" may indeed survive till the present epoch. These nuggets may well be good candidates for baryonic dark matter in the universe [9, 10, 11]. The strange nuggets may also provide closure density without violating the basic premise of nucleosynthesis [10, 11].

A QN formed after the phase transition will survive up to the present epoch if it loses heat and cools without losing any significant fraction of initial baryon number.

On the basis of simple heuristic argument a QN with baryon number N_B at a time t will stop evaporating further and thus survive forever, that means, now, if the time scale of evaporation $\tau_{ev}(N_B, t) = N_B / (dN_B/dt)$ is considerably larger than the Hubble expansion time scale, $H^{-1}(t) = 2t$, of the universe. Using Chromo Electric flux tube model N_B and dN_B/dt was calculated in ref [12]. Taking the Hubble constant $H_0 = 75 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ it was shown that with $N_{B,in} \leq 10^{43.25}$ and a flat universe, the nuggets will be unstable and evaporate completely with time. In contrast QN's with $N_{B,in} \geq 10^{43.25}$, with time do not lose any baryon and thus survive for ever. N_B considerably low than $10^{43.25}$ (say) 10^{42} evaporate very early, only a few microsecond after the phase transition from quarks to hadrons. The neutron to proton ratio in the ambient universe, evidently goes up due to the evaporation (preferably) neutrons from the surface of quark nuggets. Protons, on the other hand tend to get coulomb repelled by the ambient cosmic soup. Such differential increase or overdensity would dissipate away, primarily because of the conduction of heat into the baryon overdense region by the neu-

trinos coming from the ambient universe. This process goes on until the temperature is of the order of 1 MeV. After that epoch baryon diffusion dominates the scenario [9, 10].

As per standard big bang primordial (SBBN) nucleosynthesis, the baryons constitute only $\sim 10\%$ of the closure density ($\Omega_B \sim 0.1$). Total baryon number of 10^{50} within the horizon at a temperature of $\sim 100 \text{ MeV}$ [9] would close the universe baryonically provided these baryons do not take part in SBBN, a criteria ideally fulfilled by the QN's. This requires $N_B^{QN} \leq 10^{45.3}$ which is clearly above the survivability limit of QN's as mentioned earlier [12].

Thus, one can conclude at this stage that the baryons contained in QN's will not participate in nucleosynthesis. In the galaxy formation they would behave like planetary mass black holes.

It is also to be noted that in equilibrium the energy per quark equals the chemical potential, so that the energy per quark in strange quark matter is less than the energy per quark in zero strangeness quark matter; the strange quark matter is more tightly bound than non strange quark matter by about 100 MeV per baryon. Thus energetically it is more convenient to have QN's made of strange quarks (SQN).

What about the number density of SQN's?

It is seen [9, 10, 11] that the number density of QN's, n_{QN} is given by

$$n_{QN} \approx \frac{1968}{(vt_P)^3} \quad (1)$$

t_P is typically the percolation time and $t_P \equiv 27\mu s$ [10]. In an idealized situation where the universe is closed by the baryonic dark matter trapped in the QN's we have

$$N_B^H(t_P) = n_{QN} V_H(t_P) N_B^{QN} \quad (2)$$

where $N_B^H(t_P)$ is the total number of baryons, required to close the universe ($\Omega_B = 1$) at t_P , N_B^{QN} is the total number of baryons contained in a single quark nugget and $V_H(t_P)$ is the horizon volume ($V_H(t_P) = (4\pi/3)(ct_P)^3$). Taking $v/c = 1/\sqrt{3}$ we get $N_B^{QN} \leq 10^{-4.7} N_B^H(t_P)$. Using Eqs. 1 and 2 the conservative upper limit of the baryon number of individual QN's thus is comfortably below the number 10^{49} , so that the sizable number of QN's can be formed. Their size distribution peaks for reasonable nucleation rates at baryon number $\sim 10^{42-44}$ [10, 11] evidently stable and much lower than the horizon limit. It is also found [6] that SQN's contain 80-90% of the mass of the baryons of the universe, hinting that the large mass reservoir in the universe are contained in SQN's.

It appears that the upper limit on the baryon number of QN's that would close the universe [10] is not very sensitive to the nucleation mechanism and estimates point to the real possibility that SQN's indeed are possible candidate of cold dark matter and even can close the universe.

Initially as is well known, the radiation pressure will keep the SQN's from clumping under gravity. Once, with time the gravitational force starts dominating, SQN's will tend to coalesce under mutual gravity. Detailed calculation [11] for baryon

number b_N at the critical temperature T_{cl} (MeV), the total number N_{QN} of SQN's are compared scaled and scaled by M_\odot in Table 1. With increase in b_N , the number N_{QN} drops rapidly. ¹

Table 1: Critical temperature (T_{cl}) of SQN's of different baryon number b_N , the total number N_N of SQN's that coalesce together and their total final mass in solar mass units.

b_N	T_{cl} (MeV)	N_N	M/M_\odot
10^{40}	1.2	2.40×10^{10}	0.42
10^{42}	1.6	2.44×10^{14}	0.24
10^{44}	4.45	1.23×10^{11}	0.01
10^{46}	20.6	1.1×10^7	0.0001

It is clear however there can be no further clumping of those already clumped SQN's, the density of such objects would be too small within the horizon for further clumping.

These objects will survive the entire evolutionary history of the universe upto now.

In recent years [13], there has been experimental evidence for at least one form of dark matter - the Massive Astrophysical Compact Halo Objects (MACHO) detected through gravitational micro lensing [13]. MACHOs only manifest gravity, thus detectable by gravitational micro lensing. These cosmic objects are dark, not visible astronomically [9]. Based on [9, 10] Milky way halo MACHOs are detected in the direction of LMC-the Large Magellanic Cloud, MACHOs are expected to be in the mass range (0.15-0.95) M_\odot , more likely to be in the vicinity of 0.5 M_\odot [10, 11], much higher than the fusion threshold of 0.08 M_\odot . For very good reasons MACHOs are unlikely candidates for white dwarfs, not even blue dwarfs. The suggestions [15] that they could be simply primordial black holes, can be ruled out since existence of primordial black holes need order of magnitude fluctuation, improbable in reality !

From all these considerations the clumped SQN's, still surviving from the primordial epoch of quark hadron phase transition in the universe are the MACHO 's; again indicating that QN's with baryon number b_N even less than 10^{42} is certainly a possibility, within the scope of the uncertainty of the parameters [9].

The relics of the first order cosmic phase transition from quarks to hadrons can thus lead to stable strange quark nuggets, candidates for cold dark matter, appearing in the form of MACHOs already experimentally observed.

The very existence of SQN's in the form of MACHO's further substantiates the scenario of a first order phase transition leading to exotic SQN's. What is the structure of the distributions of SQN's in the universe?

One possible scenario could be that the clumped SQN's will be attracted to each other by gravity, grow in size by devouring non strange objects and turning them strange, since energetically lower energy is the most plausible scenario. Such a scenario in extreme conditions has already been observed by

¹ Most significant and realistic contribution comes from $b_N \equiv 10^{42}$, for 10^{46} , M/M_\odot is already too small; for $b_N \equiv 10^{40}$, it is unlikely but as mentioned in this limit of uncertainty.

the composite image, showing the ring like dark matter distribution superimposed on the optical view of galaxy cluster C10024X17[14] The other more probable scenario is that lumps of SQN's are still floating around in our galaxy in no structured form. To our knowledge structured links of MACHOs are not known as yet.

3. The Neutron Star

The entire discussion so far, is related to very early universe when the baryonic chemical potential $\mu \rightarrow 0$ and the temperature is of the order of (150-200) MeV. The cosmological big bang is played out at LHC albeit in a miniature scale, with the little bangs between two nuclei. As is well known the big bang is a display of gravity, space and time where as the little bang is essentially to do with confinement and subsequently to deconfinement in extreme conditions.

On the other extreme end of the phase diagramme lies a domain of very high baryonic density but at rather low temperature, a scenario for neutron star matter, of compressed baryonic matter and a temperature, very near zero.

It is widely conjectured [15, 16, 17] that the quark gluon sector of such matter may indeed consist of "colour super conductors" and high density hadronic (neutron) matter or hybrid matter in the hadronic sector[17].

We study the spin down behaviour of a rotating neutron star with the realisation that changes in the internal structure as the star spins down, will be reflected in the moment of inertia and hence the deceleration. In this letter we are not considering the "recycling" scenario of binary system.

During the spin down of a (say) millisecond neutron star, the central [16] density increases with decreasing centrifugal force; leading to a phase transition from the somewhat incompressible nuclear matter to the highly compressible, perfect fluid, quark matter in the stellar core.

Indeed as the bulge of quark matter in the stellar core increases in dimension, a perfect fluid of QCD colour will set in, and, the perfect colour fluid will splash into hadronic matter transforming more of hadronic matter to colour superconducting quark matter. After the quark gluon matter dominates in the core, the star would contract significantly and its moment of inertia decreases sharply, a common signature of phase transition from confined to deconfined matter.

Glendenning [16] sometime ago pointed this phenomenon by introducing the braking index; for completeness we quote, $n(\Omega) = \dot{\Omega}\Omega/\dot{\Omega}^2 = 3 - \frac{3I'(\Omega)\Omega + I''(\Omega)\Omega^2}{2I(\Omega) + I'(\Omega)\Omega}$, for a frequency of Ω . The other notations have their usual meaning.

During phase transition $n(\Omega)$ will deviate [16] substantially from its canonical value $n = 3$. Since the growth is paced by slow spin down of the pulsar, the signal of phase transition will be "on" over a long time-the slow increase in the entropy in the new phase (quark) will lead to slowing down of the spin.

The nature of the phase transition from hadrons to quarks in a neutron star, thus is unique and very different; from the experiments carried out on our earth. The continuous process of phase transition closely resembles cross over but not exactly

identical. It is felt that by means of designing ingenious experiments conducted by "CBM" type of detector this novel matter can be discovered; one possibility of course is to study "CBM" but at cooler environment, analogous to the core of neutron star.

By now a very large number and variety of neutron stars have been discovered [15, 17]. Thus it is quite realistic to see the relationship of M (neutron star) and the radius R and try to extract the equation of state more precisely. For the internal quark structure we need a softer equation of state (quark matter being more compressible) and even more compact star. This is being explored in [18].

Recently [19, 20] existence of the massive Pulsar PSR J1614-2230 has been reported with mass of $1.97 \pm 0.04 M_{\odot}$, the structure of the neutron star has gone through substantial rethinking. In particular, the highest mass neutron star that can be supported against collapse depends very sensitively on the underlying equation of state. In particular, if quark, hyperon or boson degrees of freedom are excited at high densities the equation of state softens and cannot support massive neutron star [17]. Even a single event of a massive neutron star can therefore strongly constrain the fundamental properties of ultradense matters.

Following the phenomenological equation of state proposed by Alford *et al.* [21], Özel *et al.* [20] demonstrated that strongly interacting quark core can sustain the large mass very high density inside the neutron star such a scenario is plausible. On the otherhand strongly interacting quark matter has already been discovered at RHIC and LHC, indicate the quark gluon plasma formed after the collision of two nuclei will not lead to non-interacting fermi gas but strongly interacting fluid. It has been suggested by the four RHIC experimental groups [22] that the best parameters for describing what they found in the system created in Au+Au collisions was one usually applied to liquids-namely, the ratio of η/s for its shear viscosity to its entropy density. That ratio turned out to be nearly zero, making the system one of the first experimentally accessible "perfect fluid" ever observed in the laboratory.

It will be of some interest to compare and contrast the "perfect fluid" property of the quark matter in the microsecond universe with the "perfect fluid" of the core of the neutron star.

It is interesting to note that for the early universe, we have a depleting quark matter as hadronisation progress and the universe expands in space and time. From the canonical value of $\eta/s \leq 1/4\pi$, with hadronisation η/s will go on increasing as pointed at Roy *et al.* [23].

Eventually, the SQN's will be floating in a dilute hadronic fluid, which is not so perfect, facing more viscous drag than its quark matter counter part.

In the case of the neutron star however the scenario is opposite, more hadrons will be transformed to quarks so η/s will decrease towards the canonical value $\eta/s \leq 1/4\pi$. For the neutron star however an approximate estimate of $\eta/s \sim T\lambda_F c_s$ will indicate that with very low value of $\lambda_F \equiv (\rho\sigma)^{-1}$ with high (very high ρ) and extremely low temperature η/s for the quark core of the star with $c_s \sim 1/\sqrt{3}$ (say) may well go down below the generic value $1/4\pi$ and close to zero [24] or indeed go to zero making the core, really a perfect fluid splashing on the

membrane [6] of hybrid hadronic matter and quark core. The discovery of massive neutron star, $1.97 \pm M_{\odot}$ further substantiates this view point. It will be of great interest to explore this in future.

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