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Revisiting the boiling of primordial quark nuggets at nonzero chemical potential

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ABSTRACT

The boiling of possible quark nuggets during the quark-hadron phase transition of the Universe at nonzero chemical potential is revisited within the microscopic Brueckner–Hartree–Fock approach employed for the hadron phase, using two kinds of baryon interactions as fundamental inputs. To describe the deconfined phase of quark matter, we use a recently developed quark mass density-dependent model with a fully self-consistent thermodynamic treatment of confinement. We study the baryon number limit $A_{\rm boil}$ (above which boiling may be important) with three typical values for the confinement parameter D. It is firstly found that the baryon interaction with a softer equation of state for the hadron phase would only lead to a small increase of $A_{\rm boil}$. However, results depend sensitively on the confinement parameter in the quark model. Specifically, boiling might be important during the Universe cooling for a limited parameter range around $D^{1/2} = 170$ MeV, a value satisfying recent lattice QCD calculations of the vacuum chiral condensate, while for other choices of this parameter, boiling might not happen and cosmological quark nuggets of $10^2 < A < 10^{50}$ could survive.

1. Introduction

It has long been proposed that much of the baryon number (A) of the Universe is condensed into the quark phase (usually called quark nuggets, QNs) during the quark-hadron phase transition [1]. To survive in the hot QCD medium (~ 150 MeV), a QN of a certain size must outlive two decay processes, namely surface evaporation [2] and boiling [nucleation of hadronic bubbles (HBs)] [3,4]. The former is generally very efficient when the environment is transparent to neutrinos, and the details mainly depend [2] on the dynamic properties of the neutrino-driven cooling, for example the neutrino opacity. Our interest lies in the latter case, i.e., the boiling of QNs into hadrons, which is closely related to the underlying microscopic physics of the quark-hadron phase transition.

In one of the earliest studies, Alcock & Olinto [3] described nucleons in terms of an ideal gas, and assumed that the pressure in the strange-quark matter would be contributed entirely by the thermal spectrum of light particles (electrons, neutrinos, and photons). Based on the idea that if the total surface area of HBs exceeds the QN surface area, boiling would be inefficient, they found a baryon number minimum $A_{\rm boil}$ above which boiling is important, and concluded that this limit must be as high as 10^{46} - 10^{49}. They have furthermore treated the surface tension of QNs, σ, as a free parameter and obtained for it an unusually large lower limit, namely $(178\ {\rm MeV})^3$, which would mean that almost all QNs could not survive boiling. Later Madsen & Olesen [4] treated the hadron phase as a Walecka-type interacting neutron–proton–electron (npe) gas and also introduced the fermion pressure in the quark phase using the MIT bag-like model [5]. They found a rapid dependence of $A_{\rm boil}$ on the parameters (σ, B), where B is the bag constant. They argued that QNs may survive boiling for some choice of (σ, B), and that therefore for such a case boiling is not the dominant decay process for QNs, compared to the evaporation mentioned above. In the recent work of Lugones & Horvath [6], quark pairing and the curvature energy were introduced in the quark phase and it was concluded that both boiling and surface evaporation would be suppressed by the pairing gap. The authors also argued that boiling

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might be unlikely for intermediate temperatures ($T < T_\Delta \sim 0.57\Delta$), where Δ is the pairing gap.

Clearly, the most important aspect for the boiling problem is how to treat the strong interaction between quarks (in the quark phase) and between hadrons (in the hadron phase). This will evidently affect the chemical composition of the two phases, and lead to different conclusions of the occurrence of boiling. The aim of this work is hence to employ the hadronic and quark EOSs based on the most advanced microscopic approaches. The results should have important impacts on the conclusions reached before [4] based on the phenomenological nuclear many-body theory. We can also get more insight from the comparison of the calculated results using different versions of baryon interactions, that is, to achieve a better understanding on the relation between the cosmological QCD phase transition and the underlying EOS.

For the quark phase, the simple MIT bag model [5] used in previous studies [4,6] is actually not well justified, since it includes no interactions between quarks (quarks are asymptotically free within a large bag). Also, the model itself was originally proposed in order to treat quark confinement, therefore at any finite temperature, a more self-consistent scheme to treat thermal radiation and particle-antiparticle creation is needed. In the present study this is achieved by a fully self-consistent thermodynamic treatment of confinement, i.e., a recently developed quark mass density-dependent (QMDD) model [7,8]. This model has been widely used in the last few years for the structures and the viscosity of compact stars [9–13].

On the other hand, thanks to the rapid progress in the treatment of microscopic theories of the nuclear matter equation of state (EOS) in recent years, a detailed study of the hadron phase is by now possible, and we in the present work therefore can treat it much more accurately than in the phenomenological relativistic mean-field model used before [4]. We employ the parameter-free microscopic Brueckner–Hartree–Fock (BHF) approach that has been widely used for the study of dense stellar matter and neutron star properties [9,14–26], along with two cases of baryon interactions as inputs. They have the same nucleonic two-body potentials, Argonne v18 [27], but different three-body forces (TBF), i.e., the phenomenological Urbana model [28,29], and a microscopic TBF constructed from the meson-exchange current approach [30]. Both of them reproduce fairly well the saturation point of symmetric nuclear matter around the saturation density of 0.17 fm^{-3}, and also fulfill the recent 2-solar-mass neutron star mass measurement [31,32]. They, however, give a very different high-density EOS ($> 0.4\ \mathrm{fm}^{-3}$) [14]. In particular, the microscopic TBF turns out to be more repulsive than the Urbana model at high densities, and the discrepancy between the two predictions becomes increasingly large as the density increases. Since the threshold of the quark-hadron transition is essentially determined by the stiffness of different hadron EOSs, we should keep in mind that the EOS from the microscopic TBF is stiffer than that of the phenomenological one. Hereafter, we refer to "stiff EOS" as the one with the microscopic TBF, and to "soft EOS" as the one with the phenomenological TBF. Calculations are mainly done using the microscopic TBF, and results with the phenomenological TBF are presented as well in several cases for comparison.

Here we have neglected the possible appearance of hyperons and pion or kaon condensates in the hadron phase, which in general might soften the high-density EOS. How to confront them with the high-mass neutron stars is an important topic discussed frequently in recent papers [17,33,34]. It would be straightforward to include the strangeness in the hadron phase in a subsequent study, once the controversial high-density EOS is clarified.

Let us also mention here that the subject of study of the boiling of QNs (into hadrons), in principle demands that the QCD phase transition is of first order (see for instance [6] and references therein). Lattice QCD studies over the past years have however reached the conclusion that, for physical quark masses and a vanishing baryon chemical potential μ, this transition is rather a smooth crossover than a first order phase transition [35–37]. If the Universe follows the "standard" scenario and undergoes the QCD phase transition with only a very small μ, this would mean that QNs could not have been created and the discussion of their properties would thus be irrelevant for the Universe that we live in. It should however be stressed here that there is room for an alternative scenario, which has been discussed in the literature [38–41] as little inflation. In this case, the Universe follows a path with larger μ and can therefore undergo a first order phase transition as the QCD phase diagram is expected to have a critical endpoint at some finite value of μ, above which the quark-gluon plasma and hadron gas phases are separated by a first order phase transition line. The creation of QNs can hence not be ruled out and studying their properties may still be of relevance for the physics of our Universe.

The paper is organized as follows. In Section 2, we establish our physical model and describe in details the numerical methods for the calculation. In Section 3, numerical results are discussed. We present our main conclusions in Section 4.

2. The model

2.1. Boiling of QNs

In the hot QCD medium, the hadron gas may be energetically favored in thermal fluctuations, and bubbles of hadronic gas would nucleate throughout the volume of the produced nuggets of strange matter. This process is called "boiling of QNs". If boiling happens, the QN would dissolute into hadrons and disappear in the Universe.

Following the estimation using classical nucleation theory by Alcock & Olinto [3], the work done to form a bubble of radius r composed by the hadronic phase inside the quark phase is

$$W = -\frac{4}{3}\pi r^3 \Delta P + 4\pi\sigma r^2, \tag{1}$$

where σ is the QN surface tension. We follow Madsen & Olesen [4] and self-consistently calculate the surface tension from all fermion species ($i = u, d, s, e$) as:

$$\sigma_i = \frac{3T}{8\pi} \times \int_0^\infty \left(1 - \frac{2}{\pi}\arctan\frac{k}{m_i}\right) \ln\left[1 + \exp\left(-\frac{e_i(k) - \mu_i}{T}\right)\right] k dk. \tag{2}$$

where the energy $e(k)$ is given as $e(k) = \sqrt{k^2 + m_i^2}$ with m_i (μ_i) being the mass (chemical potential) of component i. T is the temperature. $\Delta P = P_H - P_Q$ is the pressure difference between the hadron phase (with a pressure of P_H) and the quark phase (with a pressure of P_Q). Assuming that the phase transition is first order, its properties are calculated from the pressure difference between the two phases based on the chemical equilibrium condition:

$$\mu_Q(P_Q) = \mu_H(P_H) \equiv \mu \tag{3}$$

where μ_Q and μ_H are the baryon chemical potentials for the hadron and quark phases, respectively.

Specifically, as illustrated in Fig. 1, besides the common pressures from thermal photons and neutrinos, P_H is contributed by hadrons and $e^\pm$ pairs which will be dealt as accurately as possible here, P_Q constitutes a nonthermal pressure from u, d, s quarks and $e^\pm$ pairs. Since the pressure of the quark phase, P_Q, is equal to the pressure in the Universe (mainly contributed by thermal photons,