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Dynamical Evolution of the Universe in the Quark-Hadron Phase Transition and Nugget Formation

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Abstract. We study the dynamics of first-order phase transition in the early Universe when it was $10 - 50\mu s$ old with quarks and gluons condensing into hadrons. We look at the evolution of the Universe in small as well as large super cooling scenario.

It is well known that a phase transition from quark gluon plasma to confined hadronic matter must have occurred at some point in the evolution of the early Universe, typically at around $10 - 50\mu s$ after the Big Bang. This leads to an exciting possibility of the formation of quark nuggets through the cosmic separation of phases. Below the critical temperature T_c of the phase transition, the QGP super cools and the transition proceeds through the bubble nucleation of the hadron phase. As the hadronic bubbles expand, they heat the surrounding plasma, shutting off further nucleation and the two phases coexist in thermal equilibrium. The hadron phase expands driving the deconfined quark phase into small regions of space and it may happen that the process stops after the quarks reach sufficiently high density to provide enough pressure to balance the surface tension and the pressure of the hadron phase. The quark matter trapped in these regions constitute the quark nuggets. The number of particles trapped in the quark nugget, its size and formation time are dependent sensitively on the degree of super cooling. The duration of the phase transition also depends on the expansion of the Universe and on other parameters like the bag pressure B and the surface tension σ.

Here we calculate the nucleation rate and quantitatively study what happens when the temperature drops to T_c. This nucleation rate is used to solve a set of rate equations to study the time evolution of the quark-gluon phase as it converts to hadronic matter in an expanding Universe. A novel feature of this method is that reheating of the plasma during phase transition is included in the calculations along with bubble growth in the expanding Universe. This allows for the completion of the transition and all relevant quantities can be evaluated as a function of time and temperature. The fraction of the Universe $h(t)$ which has been converted to hadronic phase at the time t takeing bubble growth into account. $h(t)$ is given by

$$h(t) = \int_{t_c}^{t} I(T(t'))[1 - h(t')]V(t', t)\left[\frac{R(t')}{R(t)}\right]^3 dt' \tag{1}$$

where $V(t', t)$ is the volume of the bubble at t' nucleated at t. The two Einstein's equations which couple time evolution of temperature to the hadron fraction $h(t)$

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are given by.

$$\frac{\dot{R}}{R} = \sqrt{\frac{8\pi G}{3}} \rho^{\frac{1}{2}} = -\frac{1}{3w}\frac{d\rho}{dt} \tag{2}$$

We numerically integrate the coupled dynamical equations (1) and (2) to study the evolution of the phase transition. We find that reheating takes place as nucleation starts with the release of latent heat and as σ increases, the super cooling is larger and reheating is slower. The transition takes much longer to complete with more chance of nugget formation. The number of quarks in the horizon N_{qH} at time t is $N_{qH} \sim n_q(\frac{4}{3}\pi t^3) \sim (\frac{n_q}{n_\gamma})\frac{2\zeta(3)}{3\pi^2}T^3 4\pi t^3$ and we find that for all interesting cases $N_q \leq N_{qH}$ and this number is very sensitively dependent on the surface tension. Physically it is possible to have $N_{qH} \geq N_q \geq 10^{52}$ for some values of the parameters B and σ. In table I below we list some physical quantities for some representative values of B and σ.

$B^{1/4}$ MeV	σ $MeV fm^{-2}$	T_c MeV	t_f μs	T_f MeV	N_q	N_{qH}	l_n m
235	50	169	12.1	169	2.6×10^{28}	7×10^{52}	8×10^{-3}
145	57.1	104.4	34.7	99.9	9.4×10^{35}	3.4×10^{53}	4.6
125	57.1	90	56.1	78.8	1.1×10^{39}	7.3×10^{53}	63
125	77	90	1511.8	17.9	6.3×10^{48}	1.6×10^{56}	4.9×10^{5}
100	39.5	71.9	2595	13.9	1.2×10^{50}	3.8×10^{56}	8.4×10^{5}
113	57.1	81.3	5138	12.3	9×10^{49}	2×10^{57}	1.7×10^{6}

In conclusion, If the nuggets studied above are indeed formed in a much cooler environment, they could contribute significantly to the missing mass in the Universe and be candidates for dark matter.

References

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