# Effect of pre-existing baryon inhomogeneities on the dynamics of the cosmic quark-hadron transition.

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*1) Baryon inhomogeneties in the early universe.*

*2) First order quark-hadron transition in the early universe.*

*3) Effect of inhomogeneties on the QCD phase transition.*

*4) Generation of inhomogeneties before the QCD phase transition.*

*5) Conclusions.*

# Baryon inhomogeneties in the early universe.

Baryon inhomogeneties are generated in the early universe during :

a) Epoch of baryogenesis.

b) Quark - Hadron transition.

If they are present during nucleosynthesis, they affect the calculated abundances of the light elements.

Inhomogeneities produced around electroweak scale usually get wiped out by the processes of neutrino inflation and baryon diffusion by the nucleosynthesis epoch.

Detailed study by Jedamzik and Fuller shows that large amplitude inhomogeneities survive relatively unchanged upto the quark hadron transition.

We study the effect of such pre-existing baryon inhomogeneities on the quark - hadron transition.

## Characteristics of the baryon lumps.

**Baryonic inhomogeneities have higher baryon density and lower temperature than the background.**

**The condition for pressure equilibrium between the outside and inside the lump is given by,**

$$\frac{1}{3}\epsilon + 9N_q^{-1}\frac{n_b^2}{T^2} = \frac{1}{3}\epsilon' + 9N_q^{-1}\frac{n_b'^2}{T'^2}$$

$\frac{\epsilon}{3}$ , $\frac{\epsilon'}{3}$ **are the radiation pressures due to all the relativistic particles including leptons and photons in the two regions.**

$\epsilon = g_{eff}aT^4$ **and** $g_{eff}(\simeq 51)$ **is the effective degrees of freedom in the quark-gluon plasma phase.**

**Temperature difference between baryon lumps and background is given by :**

$$\frac{\delta T}{T} = -\frac{27}{4g_{eff}aT^4}\frac{n_b^2}{T^2}\frac{1}{N_q}[(\frac{n_b'}{n_b})^2 - 1]$$

**For** $T \sim 170$ **MeV, and for** $(\frac{n_b'}{n_b})^2 >> 1$ **we get,**

$$\Delta T' \equiv \frac{\delta T}{T} = -3 \times 10^{-19} \times (\frac{n_b'}{n_b})^2.$$

**Difference in the baryon number density changes the baryon chemical potential within the overdense baryonic lumps.**

$$\frac{\mu}{T} \sim 12 \times \eta,$$

**Since chemical potential $\mu$ is different on the two regions,critical temperature $T_c$ will also be different.**
**For non-zero chemical potential the $T_c$ in the different regions can be obtained using the Gibb's criterion for a first order phase transition.**

$$P_q = P_\pi + P_N$$

**where**

$$P_q = \frac{37}{90}\pi^2 T^4 + (\frac{\mu}{3})^2 T^2 + \frac{1}{2\pi^2}(\frac{\mu}{3})^4 - B,$$

$$P_\pi = \frac{3m^2T^2}{2\pi^2} \sum_{k=1}^{\infty} \frac{K_2(\frac{km}{T})}{k^2},$$

**and**

$$P_N = \frac{2M^4}{3\pi^2} \int_0^1 \frac{u^4 du}{(1-u^2)^3} [f(u;T,\mu) + f(u;T,-\mu)].$$

$P_q \longrightarrow$ **pressure in the quark-gluon phase,**

$P_\pi \longrightarrow$ **pressure of pions**

$P_N \longrightarrow$ **pressure of nucleons.**

$K_2(\frac{km}{T}) \longrightarrow$ **modified Bessel function of the second kind**

$$f(u;T,\mu) = (exp\frac{[M/(1-u^2)^{1/2} - \mu]}{T} + 1)^{-1}$$

$M = 940$ **MeV is the nucleon mass and** $m = 140$ **MeV is the pion mass.**

# The quark-hadron transition in the early universe.

**For a first order quark - hadron transition, the probable sequence of events is :-**

**1) Supercooling of the quark-gluon plasma** $(\Delta T_{sc})$.

**2) Nucleation of hadronic bubbles and their rapid growth** $(\Delta T_n)$.

**3) Collisions of bubbles with shocks from other bubbles.**

**4)Reheating of the plasma due to latent heat released so that bubble nucleation is shut off.**

**After this Universe maintains a constant temperature and goes on expanding by converting the QGP phase to the hadronic phase. This is known as the *slow combustion phase.***

**The duration of these events depends on the various parameters, such as surface tension** $\sigma$ **and the latent heat** $L$.

**We consider the values :-**

$\sigma \sim 0.015 T_c^3$ **and** $L \sim 3 T_c^4$

**Using these values one can estimate :**

$$\Delta T_{sc} = 1 - \frac{T_{sc}}{T_c} \simeq 10^{-4}$$

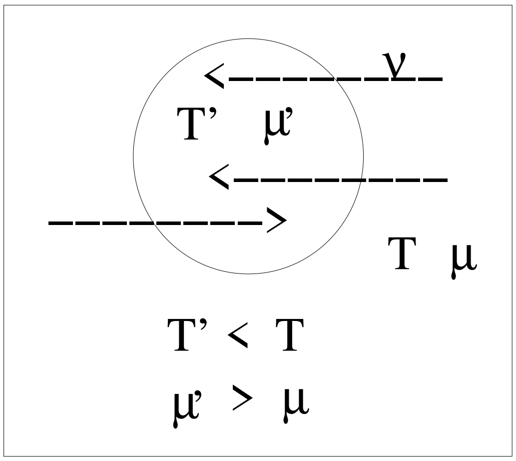
$$\Delta T_n \simeq 10^{-6}$$

**If** $\Delta t_n$ **be the time duration corresponding to** $\Delta T_n$ **then**

$$\Delta t_n \simeq 10^{-5} t_H$$

**where** $t_H \simeq 10^{-6}$ **sec is the Hubble time**

# Effect of inhomogeneties on the QCD phase transition.




The value of critical temperature $T_c$ at zero chemical potential is $T_c \simeq 172$ MeV and background $\mu \sim 10^{-6}$ MeV

For $\frac{n'_b}{n_b} = 10^7$, $\mu \sim 14$ MeV.

$$\frac{T' - T}{T} \equiv \Delta T' \simeq -4 \times 10^{-5}.$$

Similarly the difference in $T_c$'s is given by,

$$\frac{T'_c - T_c}{T_c} \equiv \Delta T'_c \simeq -4 \times 10^{-5}$$

Assuming similar supercooling in both regions as well as similar nucleation rates :

$$T'_{sc} = (1 - 4 \times 10^{-5}) \times T_{sc}$$

The difference between $T'_{sc}$ and $T_{sc}$ is of the same order as the temperature difference between the lump and the background.

**Neutrinos pump in heat which increases the temperature in the lumps temporarily until it again cools down and achieves pressure equilibrium.**

**Timescale for the lump to attain pressure equilibrium is given by**

$$\Delta t_p = R/c_s,$$

**where, $c_s \longrightarrow$ sound velocity and $R \longrightarrow$ size of the lump.**

**For $c_s = \frac{1}{\sqrt{3}}$, and $R \sim 1$ cm**

$$\Delta t_p \sim 6 \times 10^{-11} sec. > \Delta t_n \sim 10^{-5} t_H = 10^{-11} sec.$$

**We obtain the temperature rise due to the heat deposited in the lump for a time duration $\Delta t_n$ which is the timescale of bubble nucleation in the surrounding region.**

**For $R \sim \lambda$ the neutrino radiation can be approximately considered to be perfectly absorbed throughout the lump,**

$$\frac{dE}{dt} \simeq 4\pi R^2 \Phi$$

**where $\Phi$ is the net energy flux into the lump.**

$$\Phi = \sum_i \rho_i(T) \frac{\delta T}{T}$$

**Keeping the volume ($V = \frac{4}{3}\pi R^3$) constant, the temperature rise is given by,**

$$V g_{eff} a 4T^3 \frac{dT}{dt} = 4\pi R^2 g_\nu a T^4 \times 3 \times 10^{-19} (\frac{n_b'}{n_b})^2$$

**Substituting all the values we get,**

$$\frac{dT}{T} = 0.4 \times 10^{-19} (\frac{n_b'}{n_b})^2 \times \frac{dt}{R}$$

**For $R = 1$ cm and $dt = \Delta t_n = 10^{-11}$ sec we get,**

$$\frac{dT}{T} \sim 10^{-20} (\frac{n_b'}{n_b})^2 \quad > 10^{-6} \quad \text{for} \frac{n_b'}{n_b} > 10^7$$

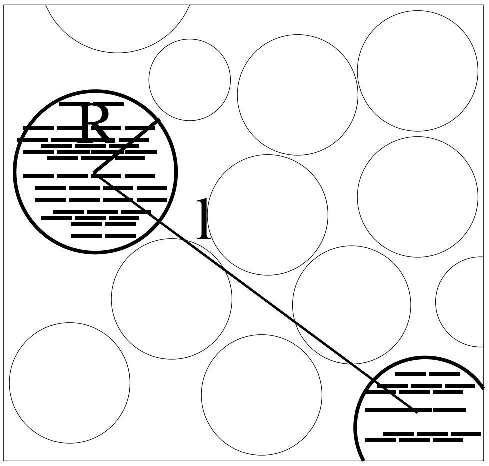
**Temperature rise is of the same order of magnitude as $\Delta T_n$ which is the temperature interval below $T_{sc}$ in which bubble nucleation process shuts off.**

**Therefore no possibility of bubble nucleation in the baryon overdense lump**

**Subsequently reheating outside increases $T$ in the lump further, keeping bubble nucleation shut off.**

**The pre-existing baryon inhomogeneities have a very high $\frac{n_b}{s}$. Hence the fraction of volume occupied by these inhomogeneities must be very small.**

**Actually two processes will go on simultaneously:**




**The fraction of volume occupied by the high density regions is roughly given by**

$$f_H = (\frac{R}{l})^3.$$

$$f_H n_H + (1 - f_H) n_L = n_b$$

**For $R \ll L$, we have $f_H \ll 1$, hence,**

$$n_L \simeq n_b - f_H n_H$$

**For $n_b = 10^{-10} \times s$ and $n_H = 10^{-3} \times s$, if we want to have $n_L \sim 10^{-10} \times s$ we must have, $f_H < 10^{-7}$.**

**So the condition for the pre-existing inhomogeneities to have a negligible effect on the total baryon number turns out to be,**

$$(\frac{R}{l})^3 \leq 10^{-7}.$$

**For $R = 0.1$ cm, $l \geq 20$ cms**

**For $R = 0.01$ cm $l \sim 2$ cms**
**In such situations at least 50% of the baryon number can get concentrated in these pre-existing inhomogeneities.**

**We may thus conclude that due to this phenomenon pre-existing baryon inhomogeneities get enhanced during the quark - hadron transition.**

## Generation of large baryon inhomogeneities before the QCD transition.

**Inhomogeneties may be generated by :**

- **Electroweak Strings :**

  * *By changing helicity of the evolving electroweak string network.*

  * *By decay in an external magnetic field.*

- **Superconducting strings :**

  *Large superconducting string loops (formed around the TeV scale) decaying into vortons and generating baryon number when these vortons subsequently decay.*

- **Decay of Domain walls.**

- **Evaporation of Primordial black holes.**

- **First order electroweak phase transition seeded by impurities can generate inhomogeneities of lengthscale $10^{-3}$ cm at the electroweak epoch, (which translates to about 1 cm at the QCD epoch)**

## Conclusions

We have shown that the presence of baryon inhomogeneities alter the dynamics of the quark-hadron transition.

In general, baryon inhomogeneities grow in size due to neutrino heating and their amplitude decreases.

We show that there is a possibility that not only do the inhomogeneities grow in size but their amplitude also increases during the quark - hadron transition.

Since the presence of inhomogeneities during nucleosynthesis affects the calculated abundances of light elements, constraints may be derived on production of large inhomogeneities present before the quark hadron transition from our scenario.