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Baryon inhomogeneities due to cosmic string wakes at the quark–hadron transition

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Abstract. Baryon inhomogeneities generated during the quark–hadron transition may alter the abundances of light elements if they persist up to the time of nucleosynthesis. These inhomogeneities survive up to the nucleosynthesis epoch if they are separated by a distance of at least a few metres. In this work we present a model where large sheets of these inhomogeneities separated by a distance of a few km are formed by cosmic string wakes during the quark–hadron transition. The effect of these sheets on nucleosynthesis will also put constraints on the various cosmic string parameters.

Keywords. Cosmic string; structure formation; quark–hadron transition.

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1. Introduction

Baryon inhomogeneities generated during the quark–hadron (Q–H) transition may lead to the creation of compact baryon-rich objects as well as alter the abundances of light elements if they persist up to the time of nucleosynthesis. These inhomogeneities are generated during a first-order Q–H transition when baryon number gets concentrated in localized regions of quark–gluon plasma (QGP) between the moving bubble walls. However, it was seen that the localized lumps do not survive till the time of nucleosynthesis unless the mean separation between them is of the order of at least a few metres. Here we show that cosmic string wakes can generate baryon inhomogeneities separated by a distance of a few km at the Q–H transition which means that these will definitely survive till the nucleosynthesis epoch and affect the light element abundances.

Cosmic strings moving through matter produce wakes where density is higher than the background density. We have studied the temperature fluctuations due to these overdensities in the cosmic string wake during a Q–H transition and it's effects on the generation of baryon inhomogeneities [1]. We find that there may be sheet-like baryonic inhomogeneities spreading across the horizon (size $\simeq$ 10 km), separated by a distance of the order of a few km. Such largely separated baryonic inhomogeneities will certainly survive till the time of nucleosynthesis. As of now, there is no model known which can lead to such large values of separation. Also, by reversing the argument, one can put constraints on the various string parameters from the ratio of the abundances produced due to inhomogeneous nucleosynthesis from this model.

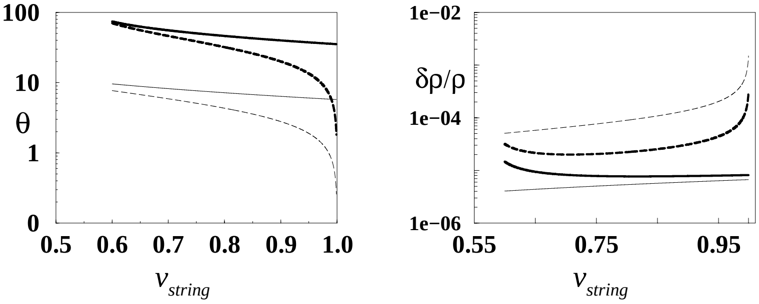

Figure 1. Plots of θ (in degrees), and $\delta\rho/\rho$, for a range of string velocities as obtained from eq. (1) (solid curves) and eq. (2) (dashed curves). Thick curves denote values corresponding to $v_{\mathrm{s}} = 1/\sqrt{3}$ while thin curves correspond to $v_{\mathrm{s}} = 0.1$.

2. Cosmic string wakes in a relativistic fluid

The space-time around a cosmic string describes a conical space, with a deficit angle of $8\pi G\mu$ [2]. The trajectories of collisionless particles bend while passing by the string. They overlap in the wedge of angle $8\pi G\mu$ behind the string leading to a wake with density twice that of the background density. One thus expects a wake with half angle $\theta_w \sim 4\pi G\mu$ and an overdensity $\delta\rho/\rho \sim 1$.

However, our interest is in the density fluctuations generated by the strings at the Q–H transition. At that time, we have a relativistic fluid which we take to be an ideal fluid consisting of elementary particles in the QGP phase, and hadrons in the hadronic phase. Generation of density fluctuations due to a cosmic string moving through a relativistic fluid have been analyzed in the literature [3]. Following these we obtain the equations for the overdensity and the half-angle of the wake in the non-relativistic case as

$$\frac{\delta\rho}{\rho_1} \simeq \frac{16\pi G\mu v_{\mathrm{f}}^2}{3\sqrt{v_{\mathrm{f}}^2 - v_{\mathrm{s}}^2}}, \qquad \sin\theta \simeq \frac{v_{\mathrm{s}}}{v_{\mathrm{f}}}, \tag{1}$$

where v_{f} is the string velocity v_{string} in the background plasma rest frame and $v_{\mathrm{s}} = 1/\sqrt{3}$ is the isentropic sound speed. For ultra-relativistic case, the equations are

$$\frac{\delta\rho}{\rho_1} \simeq \frac{16\pi G\mu u_{\mathrm{f}}^2(1+u_{\mathrm{s}}^2)}{3u_{\mathrm{s}}\sqrt{u_{\mathrm{f}}^2 - u_{\mathrm{s}}^2}}, \qquad \sin\theta \simeq \frac{u_{\mathrm{s}}}{u_{\mathrm{f}}}, \tag{2}$$

where $u_{\mathrm{f}} = v_{\mathrm{f}}/\sqrt{1-v_{\mathrm{f}}^2}$ and $u_{\mathrm{s}} = v_{\mathrm{s}}/\sqrt{1-v_{\mathrm{s}}^2}$ are the respective four-velocities. The parameters of relevance for us are θ and $\delta\rho/\rho$. In figure 1 we have given the plots of these values as obtained by the above two sets of equations. As we are interested in temperatures close to T_{c}, the speed of sound becomes very small. Thus, in figure 1 we give plots for the value of $v_{\mathrm{s}} = 1/\sqrt{3}$ (thick curves), as well as $v_{\mathrm{s}} = 0.1$ (thin curves).

We use a sample value corresponding to string velocity of 0.9 for which we take

$$\theta_w \simeq 20^\circ, \quad \delta\rho/\rho \simeq 3 \times 10^{-5}. \tag{3}$$

3. Effect of string wakes on quark–hadron transition

During the Q–H transition, the universe supercools below the critical temperature T_c (= 150 MeV), and nucleation of hadronic bubbles takes place. The amount of supercooling required is fixed by the latent heat L and the surface tension σ. We take L and σ as motivated by lattice simulations [4], ($\sigma = 0.015T_c^3$, $L \simeq 3T_c^4$) and the amount of supercooling obtained is $\Delta T_{sc} \simeq 10^{-4}$ [4]. As the bubbles expand, the universe re-heats and nucleation stops, the transition then proceeds via expansion of the nucleated bubbles. The nucleation process lasts for a temperature range of $\Delta T_n \simeq 10^{-6}$, and time duration $\Delta t_n \simeq 10^{-5}t_H$ (t_H being Hubble time). So after the phase of bubble nucleation, the universe enters into the slow combustion phase. We show that the region outside the wake enters the slow combustion phase before any bubble nucleation starts inside the wake. For this we estimate the total duration of the Q–H transition [1] and find it's value (Δt_{trnsn}) to be 14 μs. Compared to this the Hubble scale at the time when $T = T_c$ is $t_H \simeq 50$ μs.

The cosmic strings generate density fluctuations of $\delta\rho/\rho \simeq 3 \times 10^{-5}$. These translate to a temperature fluctuation of $\Delta T_{wake} \equiv \delta T/T \simeq 10^{-5}$. This temperature fluctuation is larger than $\Delta T_n \simeq 10^{-6}$. This means that nucleation of hadronic bubbles gets completed in the QGP region outside the wake, while no nucleation takes place in the wake during that time. Since $\Delta T_{sc} \simeq \Delta T_{wake}$, we conclude that the outside region enters a slow combustion phase before any bubbles can nucleate in the region of overdensity in the wake. Now it is required that the overdensity in the wake should not decrease at the time scale of $\Delta t_n \simeq 10^{-5}t_H$. The typical average thickness of the overdense region in the shock d_{shk} will be $d_{shk} \simeq \sin\theta r_H \simeq 5$ km (for a wake extending across the horizon). Here r_H is the size of the horizon ($r_H = 10$ km). A density fluctuation of this length scale (which is smaller than r_H) will propagate as a plane wave. Typical time scale (t_{shk}) for the evolution of the overdensity will be governed by the sound velocity v_s which becomes very small close to the transition temperature. Taking $v_s \simeq 0.1$, we get $t_{shk} \simeq t_H$.

Thus the density (and temperature) evolution in the shock region happens in a time scale which is large compared to Δt_n. It is also larger than Δt_{trnsn} during which the quark phase is completely converted to the hadronic phase in the region outside the wake. Here the region of study for us is the horizon volume from which the string is just exiting and the temperature of the universe is T_{sc} so that the wake extends across the entire horizon. The time duration, Δt_{lag}, by which the process of bubble nucleation in the shock region lags behind that in the region outside the wake is given by $\Delta t_{lag} \simeq 10^{-5}t_H$ [4].

Since $\Delta t_{lag} \sim \Delta t_n$, the region outside the wake enters the slow combustion phase before any bubbles can nucleate in it. So the latent heat released outside the wake will suppress any bubble nucleation in the wake, especially near the boundaries. Thus the hadronic phase is separated from the QGP phase by interfaces at the boundaries of the wake (shown in figure 2a). Transition is completed by these interfaces moving inwards from the boundaries. Moving interfaces will then trap most of the baryon number of the entire region of the wake towards the inner region of the wake. Finally interfaces merge, leading to a sheet of very large baryon number density, extending across the horizon.

However it may be that bubble nucleation is not suppressed near the center of the shock. In that case the hadronic phase spreads from inside the wake at the same time when the same phase moves in from outside the wake through the boundaries. These two sets of interfaces lead to concentration of baryon number in two sheet-like regions, with the separation between them being of the order of a km. This type of evolution is shown in

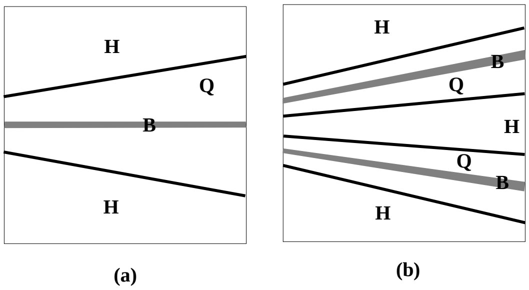

Figure 2. Q (H) denote QGP (hadronic) phase. Solid lines denote interfaces separating the phases. (**a**) Situation when no bubbles nucleate inside the wake. (**b**) Hadronic bubbles nucleate inside the wake leading to two sets of interfaces trapping QGP regions. Shaded regions (B) denote baryon inhomogeneities expected in the two cases.

figure 2b. Typical separation between such structures is governed by the number of strings in a given horizon, which is expected to be about 15. Thus these sheets will be separated by a typical distance of the order of a km which is far too large compared to any other relevant scale at that time which could dissipate such inhomogeneities [5]. These structures will then survive until the time of nucleosynthesis and affect the abundances of elements [5].

4. Conclusion

In conclusion we emphasize that cosmic string defects are generic in GUT models, and it is important to study how they affect the dynamics of the universe. We have shown that the presence of cosmic strings can lead to the formation of horizon size sheets, or pairs of sheets with large baryon number densities during the Q–H transition. These will have strong effects on the elemental abundances calculated during the nucleosynthesis epoch. Observations of these abundances may also be used to constrain cosmic string parameters and models of cosmic string network evolution. Finally, the effects described here can lead to interesting consequences for electroweak (EW) phase transition also, leading to the generation of the baryon asymmetry even for a second-order EW phase transition [6].

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