PBH and DM from cosmic necklaces

Tomohiro Matsuda

1Theoretical Physics Group, Saitama Institute of Technology, Saitama 369-0293, Japan

Abstract

Cosmic strings in the brane Universe have recently gained a great interest. I think the most interesting story is that future cosmological observations distinguish them from the conventional cosmic strings. If the strings are the higher-dimensional objects that can (at least initially) move along the compactified space, and finally settle down to (quasi-)degenerated vacua in the compactified space, then kinks should appear on the strings, which interpolate between the degenerated vacua. These kinks look like “beads” on the strings, which means that the strings turn into necklaces. Moreover, in the case that the compact manifold is not simply connected, the string loop that winds around a non-trivial circle is stable due to the topological reason. Since the existence of degenerated vacua and a non-trivial circle is the common feature of the brane models, it is important to study cosmological constraints on the cosmic necklaces and their stable winding states in the brane Universe.

1 Introduction

In this talk we will explain the cosmological consequences of the production of Dark Matter(DM) and Primordial Black Hole(PBH) from the loops of the cosmic necklaces. To begin with, I think it is fair to explain why necklaces[1] are produced in brane models, since in many papers it is discussed that “only strings are produced in the brane Universe”[2]. Of course I think this claim is not wrong, however somewhat misleading for non-specialists. To explain what is misleading in the “standard scenario”, we have a figure in Fig.1. In general, the distance between branes may appear in the four-dimensional effective action as a Higgs field of the effective gauge dynamics. At least in this case, it is natural to consider the cosmological defects coming from the spatial variation of the Higgs field, which corresponds to the “deformation” of the branes[3]. Is the spatial variation of the Higgs field unnatural in the brane Universe? The answer is, of course, no. One should therefore consider at least two different kinds of defects in brane models: One is induced by the brane creation that is due to the spatial variation of the tachyon condensation, while the other is induced by the brane deformation that is due to the spatial variation of the brane distance. Along the line of the above arguments, it is possible to construct Q-ball’s counterpart in brane models[4], which can be distinguished from the conventional Q-balls by their decay process. We therefore have an expectation that strings can be distinguished from the conventional ones, if one properly considers their characteristic features.

Now let us discuss about the validity of the conventional Kibble mechanism. Of course the Kibble mechanism is an excellent idea that explains the nature of the cosmological defect formation. However, if there is oscillation of the brane distance that may be induced by the brane inflation or by a later phase transition that changes the brane distance, the four-dimensional counterpart of the brane distance (i.e. the Higgs field) oscillates in the effective action. In the four-dimensional counterpart, defect production induced by such oscillation is already discussed by many authors, including the production of the sphaleron domain walls which otherwise cannot be produced in the Universe[3]. The defect production induced by such oscillation may or may not be explained by the Kibble mechanism, however it should be fair to distinguish it from the “conventional” Kibble mechanism.

Let us summarize the above discussion about the defect production in the brane Universe. Actually, it is possible to produce all kinds of defects in the brane Universe, however it is impossible to produce defects other than the strings simply as the result of the brane creation that is induced by the conventional Kibble mechanism. One should therefore be careful about the assumption that is made in the manuscript, which may or may not be explicit. The necklaces are produced as the hybrid of the
brane creation and the brane deformation. It should be noted that the stable loops of the necklaces that we will discuss in this talk may appear in the four-dimensional gauge dynamics, irrespective of the existence of the branes\cite{5}. The stabilization of the necklace loops is first discussed in Ref.\cite{6} for brane models and in Ref.\cite{5} for necklaces embedded in four-dimensional gauge dynamics.

In order to produce necklaces in the brane Universe, the motion in the compactified direction is important. I know that in the “standard scenario” it is sometimes discussed that the position of the strings are fixed by the potential that is induced by the supersymmetry breaking, and the position is a homogeneous parameter of the Universe because all the decay products (Typically, they are F, D, and \((p, q)\) strings) lie (at least initially) along the same plane of the original hypersurface on which the tachyon condensation took place. However, in this case one may hit upon the idea that the potential for a string cannot be identical to all the other kinds of the strings. One may therefore obtain many kinds of strings that may move independently along different hypersurfaces, with exponentially small intersection ratios. Moreover, I think it is not reasonable (but may be possible) to assume that the string motion is utterly restricted by the potential even in the most energetic epoch just after inflation. Please remember that in general the moving (inflating) brane carries kinetic energy, and the brane annihilation should be an energetic process, although one may admit that there could be exceptional scenarios. I therefore think that the decay products should have kinetic energy, which is enough to climb up the potential hill at least just after brane inflation.

Figure 1: We show how necklaces are produced despite the “standard” arguments.

2 PBH and DM from necklaces

The scenario of the PBH formation from strings is initiated by Hawking\cite{7}, who utilizes the huge kinetic energy of the shrinking loops. However, the probability of finding loops that can shrink into their small
Schwarzschild radius is very rare due to their random shape and motion, which weakens the obtained bound for the string tension up to $G\mu < 10^{-6}$. In our previous paper [hep-ph/0509061], we have just extended Hawking’s idea to the networks that include monopoles attached to the strings. It should be emphasized that both in the above scenarios, the kinetic energy of the shrinking object plays crucial role.

Now let us discuss about our new idea for producing PBHs. The most obvious discrepancy is that in our new scenario we discard the benefit of the kinetic energy. We consider stable relics that are produced from necklace loops, whose mass is large enough to turn into black holes, even after they have dissipated their kinetic energy during the loop oscillation. The stability of the loops is due to their windings around the compactified space. Of course the production of PBHs is delayed compared to the Hawking’s scenario, however the obtained bound is much stronger than the original scenario due to the high ($\sim 1$) production ratio. This new mechanism of PBH production is first advocated in hep-ph/0509062.

Let us explain how one can count the winding number of a necklace loop. Please see Fig.2 We introduce $\chi(t)$, which is the step length between each random walk that corresponds to the right or the left movers in the compactified direction. Since the left and the right movers can annihilate on the necklaces, the actual distance between “beads” becomes much larger than $\chi(t)$. We therefore introduce another parameter $d(t)$, which is the typical length between the remaining “beads”. Although the annihilation could be efficient, the simple statistical argument shows that the typical number of the beads that remain after annihilation is about $n^{1/2}$, if the initial number of the random walk is given by $n$. If the strings are in the scaling epoch, the typical length of the loops is $l(t) \sim \alpha t$ when they are disconnected from the string networks. Then one can obtain the typical mass of the stable relics, $M_{\text{coils}} \sim n(t)^{1/2} m \sim [l(t)/\chi(t)]^{1/2} m$, where $m$ is the typical mass of the beads.

Figure 2: If the windings are stabilized by the topological reason, one can obtain the typical number of the windings from the simple statistical arguments.

Here we should note that disregarding the annihilation, $\chi(t) \propto t^{-1}$ is already obtained in Ref. [3], which
means that $d(t)$ should evolve as $d(t) \sim t^{-1}$ at least during the short periods between each annihilation. Of course $d(t)$ is discontinuous at each annihilation, however the underlying parameter $\chi(t)$ is continuous and depends on time as $\chi(t) \sim t^{-1}$. Using the above ideas, we can calculate the typical mass of the stable relics that are produced from necklace loops. The calculation of the PBH density is straightforward. We have obtained the result

$$G\mu < 10^{-21} \times \left[ \frac{p}{0.01} \right]^{1/5} \left[ \frac{\gamma}{10^{-2}} \right]^{1/5} \left[ \frac{t_n}{M_p/\mu} \right]^{3/5} \left[ \frac{d(t_n)}{M_p/\mu} \right]^{3/5} \left[ \frac{m}{10^{16} \text{GeV}} \right]^{-6/5}, \quad (1)$$

where we have assumed $\alpha \sim \gamma G\mu$, and $t_n$ is the time when necklaces are produced. $p$ is the reconnection ratio that should be $\sim 1$ for the conventional cosmic strings, but $p \ll 1$ is possible in our case.

The string loops are produced at any time, and the typical mass of the stable relics depends on the time when they are produced, because the typical length scale of the string network increases with time both in the friction-dominated and in the scaling epoch. Therefore, the relics that are produced in an earlier epoch may be too light to turn into black holes. The “light” relics are the “monopoles” if the cosmic strings are D-branes. However, the “magnetic charge” of the “monopoles” may or may not be identical to the conventional magnetic charge of the electromagnetism. Therefore, they are the candidate of DM, and possibly the origin of the troublesome monopole problem only if they carry the conventional magnetic charge. In our paper hep-ph/0509062, we have examined if the DM relics can put significant bound on the tension of the cosmic strings. We have obtained the result for $m \sim M_{\text{GUT}} \sim 10^{16} \text{GeV}$,

$$G\mu < 10^{-23} \times \left[ \frac{p}{0.01} \right]^{9/10} \left[ \frac{1}{\beta_s} \right]^{9/10} \left[ \frac{10^{-3}}{r} \right]^{9/10} \quad (2)$$

where $r$ is the mass ratio between the string part and the beads on the necklaces, which becomes a constant in the scaling epoch.

The difficulty in lowering the typical energy scale is discussed in Ref. 10 for baryogenesis and Ref. 11 for the mechanism to generate density perturbations.

References

[1] A. Vilenkin and E.P.S. Shellard, Cosmic strings and other cosmological defects, (Cambridge University Press, Cambridge, 2000).

[2] See hep-th/0512062 for the most recent tutorial on this matter.

[3] T. Matsuda, JHEP 0411:039,2004; JHEP 0410:042,2004; JHEP 0309:064,2003.

[4] T. Matsuda, JCAP 0410:014,2004.

[5] T. Matsuda, hep-ph/0509062, hep-ph/0509064.

[6] T. Matsuda, JHEP 0505:015,2005; Phys.Rev.D70(2004)023502.

[7] S. W. Hawking, Phys.Lett.B231(1989)237.

[8] T. Matsuda, hep-ph/0509061.

[9] V. Berezinsky and A. Vilenkin, Rev.Lett.79(1997)5202.

[10] T. Matsuda, Phys.Rev.D66(2002)023508; Phys.Rev.D66(2002)047301; Phys.Rev.D65(2002)107302; J.Phys.G27(2001)L103; Phys.Rev.D67(2003)127302; Phys.Rev.D65(2002)103501; Phys.Rev.D65(2002)103502; Phys.Rev.D64(2001)083512.

[11] T. Matsuda, Class.Quant.Grav.21(2004)L1; hep-ph/0509063, Phys.Rev.D66(2002)107301; Phys.Rev.D68(2003)047702; JCAP 0306:007,2003; Phys.Rev.D67(2003)083519; JCAP 0311:003,2003; Phys.Lett.B423(1998)35; Phys.Rev.D68(2003)127302.