Formation & evolution of cosmic superstrings: a short review

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I will briefly review the formation and evolution of cosmic superstrings, in the context of brane-world cosmological models within M-theory. These objects can play the rôle of cosmic strings, offering a variety of astrophysical consequences, which I will briefly discuss.

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Current cosmological and astrophysical data, and in particular, measurements of the Cosmic Microwave Background (CMB) temperature anisotropies, strongly support the inflationary paradigm. However, despite its success, inflation remains a paradigm in search of a model. As the cosmological data keep improving impressively fast, it becomes urgent to find an inflationary model with a solid theoretical foundation. Since studies [1–3] on the probability of the onset of inflation indicate that it should take place in the deep quantum gravity regime, it is natural to study inflation in the process of brane interactions, within brane cosmology in string theory. If M-theory is indeed the theory of everything, it should provide a natural inflationary scenario. In this approach, one will identify the inflaton and its properties, while cosmological measurements will help to determine the precise stringy description of our universe. There is a number of cosmological models motivated by string theory. Compactification to four space-time dimensions leads to scalar fields and moduli, which could play the rôle of the inflaton field, provided they do not roll quickly; one has to provide a mechanism for moduli stabilization. Brane annihilations allow the survival only of three-dimensional branes [4,5] with the production of fundamental string (F-strings) and one-dimensional Dirichlet branes (D-strings). Thus, brane inflation [6] leads to the formation of cosmic superstrings, in an analogous way to cosmic strings, which are generically formed [7] at the end of hybrid inflation in the context of supersymmetric grand unified theories. In what follows, I will shortly review the formation and evolution of cosmic superstrings and briefly discuss their astrophysical consequences [8–11].

To illustrate the formation [12–14] of cosmic superstrings at the end of brane inflation, consider a $Dp-D\bar{p}$ brane-anti-brane pair annihilation to form a D(p-2) brane. Each brane has a U(1) gauge symmetry and the gauge group of the pair is U(1)×U(1). The daughter brane possesses a U(1) gauge group, which is a linear combination of the two original U(1)'s. The branes move towards each other and as their inter-brane separation decreases below a critical value, the tachyon field, which is an open string mode stretched between the two branes, develops an instability. The rolling of the tachyon field leads to the decay of the parent branes. Tachyon rolling leads to spontaneously symmetry breaking, which supports defects with even co-dimension. So, brane annihilation leads to vortices, D-strings, produced via the Kibble mechanism. The other linear combination disappears, since only one brane remains after the brane collision; it is thought to disappear by having its fluxes confined by fundamental closed strings. Cosmic superstrings are of cosmological size and they could play the rôle of cosmic strings.

It is worth mentioning that cosmic superstrings are not an inevitable consequence of brane inflation. There are models in which these objects do not appear, *e.g.*, inflationary models based on the condensation of an open string tachyon, or based on closed string moduli. However, there are also scenarios leading to cosmic superstring formation that do not rely on brane inflation, *e.g.*, the Hagedorn phase transition. The

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density of string states increases exponentially with their mass [15] and at a particular scale (the Hagedorn scale, close to the string scale), there is a phase transition and all the available energy goes into creating long (super-horizon) strings, as opposed to (sub-horizon) string loops. It is reasonable to expect that some of these objects survive until now. Thus, if inflation is not required, one can consider [16, 17] starting with a large universe in the Hagedorn phase, within the string gas scenario [18–20].

There is a number of differences between solitonic cosmic strings and cosmic superstrings. Cosmic strings are classical objects, assumed to share the characteristics of type-II vortices in the Abelian Higgs model. Cosmic superstrings, despite the fact that they are cosmologically extended, they are quantum objects. Numerical simulations [21, 22] of type-II strings in the Abelian Higgs model suggest that the probability that a pair of strings will reconnect, after they intersect, is close to unity. The reconnection probability for cosmic superstrings is smaller (often much smaller) than unity. The corresponding intercommutation probabilities, calculated in string perturbation theory, depend on the type of strings and on the details of compactification. For fundamental strings, reconnection is a quantum process and takes place with a probability of order g_s^2 (where g_s denotes the string tension). It can thus be much less than one, leading to an increased density of strings [23], which implies an enhancement of various observational signatures. Even though the value of g_s and the scale of the confining potential, which determine the reconnection probability for F-F collisions lies in the range between 10^{-3} and 1; for D-D collisions is anything between 0.1 to 1; for F-D collisions it can vary from 0 to 1.

Brane collisions can also produce [25, 26] bound states, (p, q)-strings, which are composites of p F-strings and q D-strings, with p, q relatively prime integers. The presence of stable bound states implies the existence of Y-junctions, where two different types of string meet at a point and form a bound state leading away from that point.

The tension of solitonic strings is set from the energy scale of the phase transition followed by a spontaneously broken symmetry which left behind strings as false vacuum remnants. Cosmic superstrings span a whole range of tensions, set from the particular brane inflation model employed. The tension of F-strings in 10 dimensions is $\mu_F = 1/(2\pi\alpha')$, and the tension of D-strings is $\mu_D = 1/(2\pi\alpha' g_s)$. In 10 flat dimensions, supersymmetry dictates that the tension of the (p, q) bound states reads [27]

$$\mu_{(p,q)} = \mu_{\rm F} \sqrt{p^2 + q^2/g_{\rm s}^2} \,. \tag{1}$$

Individually, F- and D-strings are $\frac{1}{2}$ -BPS (Bogomol'nyi-Prasad-Sommerfield) objects, each breaking a different half of the supersymmetry. Equation (1) represents the BPS bound for an object carrying the charges of *p* F- and *q* D-strings. In IIB string theory, where our universe can be described as a brane-world scenario with flux compactification, the string tension is different (*see e.g.*, Ref. [28]) from the (simple) expression given in Eq. (1) and depends on the particular choice of flux compactification.

The evolution of cosmic superstrings is a very complex issue, which depends on the brane inflation model. Let me first briefly summarise our understanding of the evolution of cosmic string networks [29,30].

The first (analytical) studies of the evolution of cosmic string networks indicated [31] the existence of *scaling*, in the sense that at least the basic properties of the network can be characterised by a single length scale, roughly the persistence length or the inter-string distance ξ which grows with the horizon. The scaling solution was supported [32] by subsequent numerical work; further investigation revealed [33, 34] however the existence of dynamical processes at scales much smaller than ξ .

If the super-horizon strings are characterised by a single length scale $\xi(t)$, the typical distance between the nearest string segments and the typical curvature radius of the strings are of the order of

$$\xi(t) = \left(\frac{\rho_{\text{super-horizon}}}{\mu}\right)^{-1/2} = \kappa^{-1/2}t .$$
(2)

Early numerical simulations confirmed that the typical curvature radius of long strings and the characteristic distance between them are both comparable to the evolution time, while they found the existence of an important small-scale superimposed on the super-horizon strings [34].

The sub-horizon loops, their size distribution, and the mechanism of their formation remained for years the least understood part of the string evolution. Recent numerical simulations, found [35] evidence of a scaling regime for the cosmic sub-horizon string loops in the radiation- and matter-dominated eras down to the hundredth of the horizon time, a result which has been confirmed [36] by analytical studies.

The evolution of cosmic superstrings is a much more involved issue. Cosmic superstring networks have not only sub-horizon and super-horizon strings, but also Y-junctions, which *a priori* may prevent a scaling solution. Moreover, one must consider a multi-tension spectrum and reconnection probabilities which can be much lower that unity. Certainly, computers are at present much more efficient than in the eighties and nineties when we performed the first numerical experiments with solitonic strings, and we obviously gained a lot of experience from those studies. Nevertheless, one must not forget that evolution of cosmic strings has been almost exclusively studied in the (simple but unrealistic) case of the infinitely thin approximation.

A number of numerical experiments [23, 37-46] have attempted to get some insight into the evolution of cosmic superstring networks, and in particular, investigate whether the bound (p, q) states may obstruct the existence of a scaling solution. In Ref. [44] for instance, the evolution of a cosmic string network was studied via numerical experiments in a simple field theory model of bound states (in an analogy to the Abelian Higgs model) which however incorporates the main features of string theory. It was found [44] robust evidence for scaling of all three components — p F-strings, q D-strings, (p, q) bound states independently of initial conditions. Scaling was confirmed from all other numerical studies.

At first, cosmic strings were regarded as completely different objects than cosmic superstrings. Cosmic strings on the one hand, stretch across cosmological distances and though exceedingly thin, they are sufficiently massive to have important gravitational effects. Cosmic superstrings on the other hand, were considered as being far too small to have any directly observable effects. This view has however considerably changed over the last few years, and it is believed that under certain circumstances, cosmic superstrings can, in the context of brane-world cosmological models, grow to macroscopic sizes and play the rôle of cosmic strings. Cosmic strings and cosmic superstrings can produce a variety of astrophysical signatures, including gravitational waves [47–49], ultra high energy cosmic rays [50], gamma ray bursts [51], radio bursts [52], cosmic 21 cm power spectrum [53], magnetogenesis [54], CMB at small angular scales [55], CMB polarization, and lensing [56, 57]. Their signatures though are quite distinct, due to the differences of the two networks, discussed earlier. In particular, since non-periodic F-strings ending on D-branes are accompanied [58] by the formation of *cusps*, it can be demonstrated [58] that pairs of Y-junctions, such as would form after intercommutations of F- and D-strings, generically contain cusps. This feature of cosmic superstrings opens up the possibility of extra channels of energy loss from a cosmic superstring network.

Unfortunatley, up to now cosmic strings as well as cosmic superstrings remain in the realm of theory, as hypothetical objects awaiting for an observational verification. Observational support of cosmic strings will confirm the validity of phase transitions in the context of grand unified theories applied in the early universe cosmology. Observational support of cosmic superstrings will justify the validity of string theory and will shed some light in the appropriate stringy description of our universe. Ongoing theoretical research will eventually unravel the evolution of cosmic superstring networks, while astrophysical observations will provide the means which may falsify the theory or enlighten the theoretical models.

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References

- [1] E. Calzetta and M. Sakellariadou, Phys. Rev. D 45, 2802 (1992).
- [2] E. Calzetta and M. Sakellariadou, Phys. Rev. D 47, 3184 (1993).
- [3] C. Germani, W. Nelson and M. Sakellariadou, Phys. Rev. D 76, 043529 (2007).
- [4] R. Durrer, M. Kunz and M. Sakellariadou, Phys. Lett. B 614, 125 (2005).

- [5] W. Nelson and M. Sakellariadou, Phys. Lett. B 674, 210 (2009).
- [6] N. T. Jones, H. Stoica and S. H. H. Tye, JHEP 0207, 051 (2002).
- [7] R. Jeannerot, J. Rocher and M. Sakellariadou, Phys. Rev. D 68, 103514 (2003).
- [8] A. C. Davis and T. W. B. Kibble, Contemp. Phys. 46, 313 (2005).
- [9] M. Sakellariadou, Phil. Trans. Roy. Soc. Lond. A 366, 2881 (2008).
- [10] M. Sakellariadou, Nucl. Phys. Proc. Suppl. 192-193, 68 (2009).
- [11] E. J. Copeland and T. W. B. Kibble, arXiv:0911.1345 [hep-th].
- [12] S. Sarangi and S. H. H. Tye, Phys. Lett. B 536, 185 (2002).
- [13] N. T. Jones, H. Stoica and S. H. H. Tye, Phys. Lett. B 563, 6 (2003).
- [14] G. Dvali and A. Vilenkin, JCAP 0403, 010 (2004).
- [15] M. Sakellariadou and A. Vilenkin, Phys. Rev. D 37, 885 (1988).
- [16] A. Nayeri, R. H. Brandenberger and C. Vafa, Phys. Rev. Lett. 97, 021302 (2006).
- [17] T. Biswas, arXiv:0801.1315 [hep-th].
- [18] R. H. Brandenberger and C. Vafa, Nucl. Phys. B 316, 391 (1989).
- [19] M. Sakellariadou, Nucl. Phys. B 468, 319 (1996).
- [20] T. Battefeld and S. Watson, Rev. Mod. Phys. 78, 435 (2006).
- [21] E. P. S. Shellard, Nucl. Phys. B 283, 624 (1987).
- [22] P. Laguna and R. A. Matzner, Phys. Rev. D 41, 1751 (1990).
- [23] M. Sakellariadou, JCAP 0504, 003 (2005).
- [24] M. G. Jackson, N. T. Jones and J. Polchinski, JHEP 0510, 013 (2005).
- [25] E. J. Copeland, R. C. Myers and J. Polchinski, JHEP 0406, 013 (2004).
- [26] L. Leblond and S. H. H. Tye, JHEP 0403, 055 (2004).
- [27] J. H. Schwarz, Phys. Lett. B 360, 13 (1995).
- [28] H. Firouzjahi, L. Leblond and S. H. H. Tye, JHEP 0605, 047 (2006).
- [29] M. Sakellariadou, Lect. Notes Phys. 718, 247 (2007).
- [30] M. Sakellariadou, Lect. Notes Phys. 738, 359 (2008).
- [31] T. W. B. Kibble, Nucl. Phys. B, 252, 227 (1985); Erratum-ibid., 261, 750 (1985).
- [32] A. Albrecht and N. Turok, Phys. Rev. Lett., 54, 1868 (1985).
- [33] D. P. Bennett and F. R. Bouchet, Phys. Rev. Lett., 60, 257 (1988).
- [34] M. Sakellariadou and A. Vilenkin, Phys. Rev. D, 42, 349 (1990).
- [35] C. Ringeval, M. Sakellariadou and F. Bouchet, JCAP 0702, 023 (2007).
- [36] J. Polchinski and J. V. Rocha, Phys. Rev. D 74, 083504 (2006).
- [37] A. Avgoustidis and E. P. S. Shellard, Phys. Rev. D, 71, 123513 (2005).
- [38] E. Copeland and P. M. Saffin, JHEP, 0511, 023 (2005).
- [39] P. M. Saffin, 2005, JHEP, 0509, 011 (2005).
- [40] A. Avgoustidis and E. P. S. Shellard, Phys. Rev. D, 73, 041301 (2006).
- [41] M. Hindmarsh and P. M. Saffin, JHEP, 0608, 066 (2006).
- [42] A. Rajantie, M. Sakellariadou and H. Stoica, JCAP 0711, 021 (2007).
- [43] J. Urrestilla and A. Vilenkin, JHEP 0802, 037 (2008).
- [44] M. Sakellariadou and H. Stoica, JCAP 0808, 038 (2008).
- [45] N. Bevis, et. al., Phys. Rev. D 80, 125030 (2009).
- [46] A. Avgoustidis and E. J. Copeland, arXiv:0912.4004 [hep-ph].
- [47] T. Damour and A. Vilenkin, Phys. Rev. D 71, 063510 (2005).
- [48] J. Hogan, Phys. Rev. D 74, 043526 (2006).
- [49] X. Siemens, V. Mandic and J. Creighton, Phys. Rev. Lett. 98, 111101 (2007).
- [50] V. Berezinsky, B. Hnatyk and A. Vilenkin, Phys. Rev. D 64, 043004 (2001).
- [51] P. Bhattacharjee and G. Sigl, Phys. Rept. 327, 109 (2000).
- [52] T. Vachaspati, arXiv:0802.0711 [astro-ph].
- [53] R. Khatri and B. D. Wandelt, Phys. Rev. Lett. 100, 091302 (2008).
- [54] D. Battefeld, T. Battefeld, D. H. Wesley and M. Wyman, JCAP 0802, 001 (2008).
- [55] A. A. Fraisse, C. Ringeval, D. N. Spergel and F. R. Bouchet, Phys. Rev. D 78, 043535 (2008).
- [56] K. Kuijken, X. Siemens and T. Vachaspati, arXiv:0707.2971 [astro-ph].
- [57] M. A. Gasparini, et. al., arXiv:0710.5544 [astro-ph].
- [58] A. C. Davis, W. Nelson, S. Rajamanoharan and M. Sakellariadou, JCAP 0811, 022 (2008)