Graviton production in the scaling of a long-cosmic-string network

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(Dated: September 26, 2011)

In a previous paper [1] we considered the possibility that (within the *early-radiation* epoch) there has been (also) a short period of a significant presence of cosmic strings. During this *radiation-plus-strings* stage the Universe matter-energy content can be modelled by a two-component fluid, consisting of radiation (dominant) and a cosmic-string fluid (subdominant). It was found that, during this stage, the cosmological gravitational waves (CGWs) - that had been produced in an earlier (inflationary) epoch - with comoving wave-numbers below a *critical* value (which depends on the physics of the cosmic-string network) were *filtered*, leading to a distorsion in the expected (scale-invariant) CGW *power spectrum*. In any case, the cosmological evolution gradually results in the *scaling* of any long-cosmic-string network and, hence, after a short time-interval, the Universe enters into the *late-radiation* era. However, along the transition from an early-radiation epoch to the late-radiation era through the radiation-plus-strings stage, the time-dependence of the cosmological scale factor is modified, something that leads to a discontinuous change of the corresponding scalar curvature, which, in turn, triggers the quantum-mechanical creation of *gravitons*. In this paper we discuss several aspects of such a process, and, in particular, the observational consequences on the expected gravitational-wave (GW) power spectrum.

PACS numbers: 04.30.-w 11.25.-w 98.80.Cq

I. INTRODUCTION

CGWs represent small-scale perturbations to the Universe metric tensor [2]. Since gravity is the weakest of the four known forces, these metric corrections decouple from the rest of the Universe at very early times, presumably at the Planck epoch [3]. Their subsequent propagation is governed by the space-time curvature [4], encapsulating in the field equations the inherent coupling between relic GWs and the Universe matter content; the latter being responsible for the background gravitational field [5].

In this context, we explore the creation of primordial GWs during the *scaling* of a long-cosmic-string network (see, e.g., [6]), i.e., in the transition from a cosmological model in which the matter content can be modelled by a two-component fluid - consisting of radiation (dominant) and cosmic strings (subdominant) - to a *pure* radiation-dominated Universe.

Cosmic strings are one-dimensional objects that can be formed as *linear defects* at a symmetry-breaking phase transition [7], [8]. If they exist, they may help us to explain some of the large-scale structures seen in the Universe today, such as the gravitational lenses [9]. They may also serve as *seeds* for density perturbations [10], [11], as well as potential sources of relic gravitational radiation [12], [13].

The presence of cosmic strings in a radiation model, is responsible for the constancy of the *effective potential* which drives the temporal evolution of a CGW, leading to a *critical value* (k_c) of the comoving wave-number, which discriminates the metric perturbations into *oscillating* ($k > k_c$) and *non-oscillating* ($k < k_c$) modes [1]. As a consequence, the propagation of CGWs through a *radiation-plus-strings* stage would leave imprints on their *power spectrum*. However, such a stage does not last very long, since, gradually, the production of loops smaller than the horizon results in the *scaling* of the long-cosmic-string network. According to this process, the linear defects form a self-similar configuration, the density of which, eventually, behaves as R^{-4} and the Universe (re)enters in the *pure-radiation* era (see, e.g., [7]).

In the present article, we study the quantum-mechanical production of *gravitons* in the transition of the Universe from an *early-radiation* epoch to the *late-radiation* era through the radiation-plus-strings stage. Several theoretical (and observational) consequences are discussed.

The paper is organized as follows: In Sec. II, we summarize the theory of CGWs propagating in curved space-time, including the implications arising from the constancy of the effective potential. In Sec. III, we take advantage of the scaling of a long-cosmic-string network to arrive at the late-radiation era. In Sec. IV, we demonstrate that, due to the modification in the time-dependence of the cosmological scale factor along this transition, the scalar curvature changes discontinuously; hence, gravitons are created, and, in Sec. V, we explore the corresponding *power spectrum*. The high-frequency part ($k > k_c$) of this spectrum acquires a *characteristic profile*, resulting in a *periodic function of the frequency*. Finally, in Sec. VI, we evaluate the (integrated) energy density of the CGWs created in the scaling of the long-cosmic-string network and we compare it with the corresponding quantity predicted by inflation (see, e.g., [12]). It is worth noting that, the energy density of the CGWs created in the transition of the Universe