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Phenomenology of the relic dilaton background

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Abstract

We discuss the expected amplitude of a cosmic background of massive, non-relativistic dilatons, and we report recent results about its possible detection. This paper is a contracted version of a talk given at the 15th SIGRAV Conference on "General Relativity and Gravitational Physics" (Villa Mondragone, Roma, September 2002).

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Phenomenology of the relic dilaton background

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Abstract. We discuss the expected amplitude of a cosmic background of massive, non-relativistic dilatons, and we report recent results about its possible detection.

1. The amplitude of the dilaton background and the dilaton coupling-strength

The aim of this talk is to discuss the production and the possible detection of a cosmic background of relic dilatons. The production is a well known string cosmology effect [1], so I will mainly concentrate here on the interaction of the dilaton background with a pair of realistic gravitational detectors [2, 3]. I will consider, in particular, the case of *massive* and *non-relativistic* dilatons, where some new result has recently been obtained [4].

Let me start by recalling that the string effective action contains, already at lowest order, at least two fundamental fields, the metric and the dilaton,

$$S = -\frac{1}{2\lambda_{\rm s}^2}\int d^4x\sqrt{-g}e^{-\phi}\left[R+(\nabla\phi)^2+\dots\right]. \qquad (1)$$

The dilaton ϕ controls the strength of all gauge interactions [5] and, from a geometrical point of view, it may represent the radius of the 11-th dimension [6] in the context of M-theory and brane-world models of the Universe. What is important, for our discussion, is that during the accelerated evolution of the Universe the parametric amplification of the quantum fluctuations of the dilaton field may lead to the formation of a stochastic background of relic scalar waves [1], just like the amplification of (the tensor part of) metric fluctuations may lead to the formation of a relic stochastic background of gravitational waves [7].

There are, however, two important differences between the graviton and dilaton case. The first is that the dilaton fluctuations are gravitationally coupled to the scalar part of the metric and matter fluctuations. Such a coupling may lead to a final spectral distribution different from that of gravitons. The second difference is that dilatons (unlike gravitons) could be massive. Since the proper momentum is redshifted with respect to the mass, then all modes tend to become non-relativistic as time goes on, and a typical dilaton spectrum should contain in general three branches: Ω_1 for relativistic modes, Ω_2 for modes becoming non-relativistic inside the horizon, and Ω_3 for modes becoming non-relativistic outside the horizon. The present energy-density of the background, per logarithmic momentum-interval and in critical units, can thus be written as follows [1]:

$$\Omega_1(p,t_0) = (H_1/M_{\rm P})^2\,\Omega_r(t_0)\,(p/p_1)^{\delta}, \qquad m<p<p_1, \qquad (2)$$

$$\Omega_1(p,t_0) = \left(mH_1/M_{\rm P}^2\right)(H_1/H_{\rm eq})^{1/2}\,(p/p_1)^{\delta-1}, \qquad p_m<p<m, \qquad (3)$$

$$\Omega_1(p,t_0) = (m/H_{\rm eq})^{1/2}\,(H_1/M_{\rm P})^2\,(p/p_1)^{\delta}, \qquad p<p_m, \qquad (4)$$

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(see also [3, 8, 9, 10]). Here m is the dilaton mass, H_1 the inflation $\to$ radiation transition scale, $H_{\rm eq}$ the radiation $\to$ matter transition scale, $\Omega_r(t_0)$ the present radiation energy-density, δ the slope of the spectrum, p_1 the maximal amplified momentum scale (i.e. the high-frequency cut-off parameter) and $p_m = p_1(m/H_1)^{1/2}$ the transition scale corresponding to a mode which becomes non-relativistic just at the time of horizon crossing. If the mass is large enough, i.e. $m > p_1 \sim (H_1/M_{\rm P})^{1/2}10^{-4}$ eV, then all modes today are non-relativistic, and the Ω_1 branch of the spectrum disappears. Note also that the relativistic branch of the spectrum is typically growing [1] in minimal string cosmology models ($0 < \delta \leq 3$), while the non-relativistic spectrum may have a flat or decreasing branch if $\delta \leq 1$.

The present amplitude of the non-relativistic spectrum is controlled by two basic parameters, H_1 and m. In minimal string cosmology models H_1 is typically fixed at the string scale, $H_1 \simeq M_{\rm s}$, and the question *"How strong is today the relic dilaton background?"* thus becomes *"How large is the dilaton mass?"* We would like to have a mass small enough to avoid the decay and to resonate with the present gravitational antennas, but large enough to correspond to a detectable amplitude. It is possible?

The answer depends on the value of the dilaton mass. From the theoretical side we have no compelling prediction, at present. From the phenomenological side, however, we know that the allowed values of mass (and thus of the range of the dilatonic forces) are strictly correlated to the strength of the dilaton coupling to macroscopic matter. We are thus lead to the related question: *"How large is the dilaton coupling?"*

For a better formulation of such a question we should recall that the motion of a macroscopic body, in a gravi-dilaton background, is in general non-geodesic, because of the direct coupling to the gradients of the dilaton field [2],

$$\frac{du^\mu}{d\tau} + \Gamma^\mu_{\alpha\beta}u^\alpha u^\beta + q\nabla^\mu\phi = 0, \tag{5}$$

induced by the effective "dilatonic charge" q of the body, which controls the relative strength of scalar-to-tensor forces. So, how large is q?

The experimental value of q, as is well known, is directly constrained by tests of the equivalence principle and of macroscopic gravity, which provide exclusion plots in the $\{m, q^2\}$ plane (see for instance [11]). From a theoretical point of view, on the other hand, there are two possible (alternative) scenarios. A first possibility is that, by including all required loop corrections into the effective action, the dilatonic charge q becomes large and composition-dependent [12]. In that case one has to impose $m \gtrsim 10^{-4}$ eV, to avoid contradiction with the present gravitational experiments, which exclude testable deviations from the standard Newton's law down to the millimeter scale [13]. The alternative possibility is that, when including loop corrections to all orders, the resulting effective charge of ordinary macroscopic matter turns out to be very small ($q \ll 1$)and universal [14]. In that case the dilaton mass can be very small, or even zero. In the following discussion we will accept this second (phenomenologically more interesting) possibility, relaxing however the assumption of universal dilaton interactions (which is not very natural, and which seems to require fine-tuning).

We shall thus assume that the relic dilatons are weakly coupled to matter, and light enough to have not yet decayed ($m \lesssim 100$ MeV), so as to be available to present observations. The amplitude of the background, as already noticed, depends however on m, and a larger mass corresponds in principle to a stronger signal. In this range of parameters, on the other hand, there is an upper limit on the mass following from the critical density bound,

$$\int^{p_1} d(\ln p)\Omega(p) \lesssim 1, \tag{6}$$

which has to be imposed to avoid a Universe over-dominated by dilatons. So, which values of mass may correspond to the stronger signal, i.e. to an (almost) critical dilaton background?

The answer depends on the shape of the spectrum. If $m > p_1$ and $\delta \geq 1$, so that all modes are non-relativistic and the spectrum is peaked at $p = p_1$, the critical bound reduces to $\Omega_2(p_1) \lesssim 1$, and implies

$$m < \left(H_{\rm eq}M_{\rm P}^4/H_1^3\right)^{1/2}, \tag{7}$$

which, for $H_1 \sim M_{\rm s} \sim 10^{-1}M_{\rm P}$, is saturated by $m \sim 10^2$ eV. This means that the density of the relic dilaton background may approach the critical upper limit for values of mass which are too large (as we shall see later) to fall within the resonant band of present gravitational detectors. If $\delta < 1$ the above bound is relaxed, but the mass is still constrained to be in the range $m > p_1$.

Let us thus consider the case $m < p_1$, assuming that the spectrum is flat enough ($\delta < 1$) to be dominated by the non-relativistic branch, peaked at $p = p_m$. The critical density bound then reduces to $\Omega_2(p_m) \lesssim 1$, and implies

$$m < \left(H_{\rm eq} M_{\rm P}^4 H_1^{\delta-4}\right)^{1/(\delta+1)}. \tag{8}$$

For $H_1 = M_{\rm s}$ and $\delta \to 0$ this bound is saturated by masses as small as $m \sim 10^{-23}$ eV, and this opens an interesting phenomenological possibility. Indeed, if the mass is small enough to fit the sensitivity range of present antennas (see the next section), the weakness of the dilaton coupling ($q \ll 1$) could be compensated by a large (i.e., near to critical) background intensity, much larger than for gravitons:

$$\Omega_{\rm grav} \lesssim 10^{-6} \ll \Omega_{\rm dil} \lesssim 1. \tag{9}$$

Massless backgrounds (like gravitons) are indeed constrained by the nucleosynthesis bound [15], which may be evaded by massive backgrounds dominated by the non-relativistic branch of the spectrum.

2. Detection of a cosmic background of ultra-light (but non-relativistic) scalar particles

Starting from the equation of motion (5) it can be easily deduced that the full coupling of dilatons to a gravitational detector is described by a generalized equation of geodesic deviation [2, 3]:

$$\frac{D^2\eta^\mu}{D\tau^2} + R_{\beta\alpha\nu}{}^{\mu} u^\alpha u^\nu \eta^\beta + q\eta^\beta \nabla_\beta \nabla^\mu \phi = 0. \tag{10}$$

A relic dilaton background can thus interact with a gravitational antennas in two ways:

(i) *indirectly*, through the geodesic coupling of the gravitational charge of the detector to the scalar part of the metric fluctuations induced by the dilatons [16];

(ii) *directly*, through the non-geodesic coupling of the scalar charge of the detector to the gradients of the dilaton background [2, 3].

The indirect coupling has gravitational strength ($q = 1$), but the amplitude of the gravitational background is expected to be (in general) highly suppressed ($\Omega \ll 1$); the direct coupling may refer to a much higher amplitude ($\Omega \lesssim 1$), but the effective charge q has to be strongly suppressed to agree with the results of the present gravitational experiments (see [2, 3]).

Taking into account both possibilities, the detection of a stochastic background of relic dilatons, with generic spectrum $\Omega(p)$, is controlled by the "signal-to-noise" ratio SNR, determined by the cross-correlation of the outputs of two antennas [3]:

$$\mathrm{SNR} = \frac{H_0^2}{5\pi^2}\left[2T\int_0^\infty \frac{dp}{p^3(m^2+p^2)^{3/2}} \frac{\Omega^2(p)\gamma^2(p)}{S_1(\sqrt{m^2+p^2})S_2(\sqrt{m^2+p^2})}\right]^{1/2}. \tag{11}$$

Here $S_1(f)$ and $S_2(f)$ are the noise power-spectrum of the two detectors, T the observation time, $\gamma(p)$ the "overlap function" in momentum space,

$$\gamma(p) = \frac{15}{4\pi}\int d^2\hat{n} F_1(\hat{n})F_2(\hat{n}) e^{2\pi i p \hat{n}\cdot(\vec{x}_2-\vec{x}_1)}, \qquad F(\hat{n}) = q e_a b(\hat{n}) D^{ab}. \tag{12}$$

F_1 and F_2 are the "pattern functions" of the two detectors, e_{ab} the polarization of the scalar wave propagating along the direction specified by the unit vector $\hat{n}$, and D^{ab} the "response tensor" taking into account the specific geometry and orientation of the arms of the detectors. The ratio (11) differs from a similar expression for gravitons [17] because of the mass, of the different polarization of the scalar wave, and of the pattern function which is in general proportional to the effective charge of the detector.

The presence of the mass, in particular, is crucial for determining the (possible) resonant response of the detectors, whose noise spectrum has a minimum inside a frequency band f_0 (typically, $f_0 \sim 10 - 10^3$ Hz for present detectors). Outside this sensitivity band the noise diverges, and the signal is negligible. Since $f = \sqrt{m^2+p^2}$, we have three possibilities.

If $m \gg f_0$ then the noise is always outside the sensitivity band, as $S(f) \gg S(f_0)$ for all modes p of the spectrum. If $m \sim f_0$ the noise, on the contrary, is within the sensitivity band for all non-relativistic modes, as $S(f) \simeq S(m) \sim S(f_0)$ for $p \leq m$. Finally, if $m \ll f_0$, then the sensitivity band may (possibly) overlap only with the relativistic branch of the spectrum, when $p = f \simeq f_0$. Taking into account these various possibilties, the analysis of the SNR induced in a pair of interferometric and/or resonant detectors leads to the following results.

1) A resonant response to a *massive*, *non-relativistic* background of scalar particles is possible, provided the mass is in the sensitivity band of the detector [3]. For the present resonant frequencies, $f_0 \sim 1$ Hz – 1 kHz, the present sensitivity is thus in the mass-range

$$10^{-15}\mathrm{eV} \lesssim m \lesssim 10^{-12}\mathrm{eV}. \tag{13}$$

2) For the differential mode of the interferometers, whose response tensor is traceless ($D^{ab}\delta_{ab} = 0$), the non-relativistic overlap function is always proportional to the relativistic one [3],

$$\gamma_{\mathrm{non-rel}}(p) = \left[p^4/(m^2+p^2)^2\right] \gamma_{\mathrm{rel}}(p), \tag{14}$$

both for the direct and indirect coupling. This proportionality factor induces a strong suppression for the SNR of non-relativistic modes, with $p \ll m$; as a consequence, the detection is in principle allowed (with the planned sensitivities of second-generation detectors) only if the spectrum $\Omega(p)$ is peaked at $p = m \sim f_0$ [3].

3) The above suppression, however, may be absent in the case of resonant mass detectors, and in particular for the geodesic (indirect) coupling of the dilaton background to the monopole mode of a sphere (whose response tensor is trivial, $D^{ab} = \delta^{ab}$). For two spheres, with spatial separation d, we have indeed [3, 4]

$$\gamma(p) = \frac{15}{2\pi}\left(\frac{3m^2+2p^2}{m^2+p^2}\right)^2 \frac{\sin(2\pi pd)}{pd}, \qquad \gamma_{\mathrm{non-rel}}(p \to 0) = \frac{9}{4}\gamma_{\mathrm{rel}}(m \to 0). \tag{15}$$

3) The response of spherical detectors to a massive stochastic background is also particularly enhanced (with respect to interferometers) for a flat enough spectrum [4]. For instance, if $\Omega \sim p^\delta$, and $\delta < 1$, then the SNR grows with the observation time like $T^{1-\delta/2}$, i.e. faster than the usual $T^{1/2}$ dependence.

In order to illustrate this final, important result, let us consider a non-relativistic, growing spectrum with slope $\delta < 1$, peaked at $p \sim m \sim f_0$. For $p \to 0$ the noise and the overlap functions of the two correlated monopole modes go to a constant, and the SNR integral (11) would seem to diverge, if extended down to the lower limit $p = 0$. The SNR integral, however, has an infrared cut-off at a finite value p_{min} determined by the *minimum resoluble frequency-interval* Δf associated to T, and defined by $\Delta f = (p^2+m^2)^{1/2} - m \geq T^{-1}$, which gives $p_{\mathrm{min}} \simeq (2m/T)^{1/2}$. When $\delta < 1$ the SNR integral is dominated by its lower limit, and this introduces the anomalous T-dependence of the signal,

$$\mathrm{SNR} \sim T^{1/2}\left[\int_{p_{\mathrm{min}}}^{m} dp p^{2\delta-3}\right]^{1/2} \sim T^{1-\delta/2}, \qquad \delta \leq 1 \tag{16}$$

(see [4] for numerical examples).

3. Conclusion

The possible production of a cosmic background of relic dilatons is a peculiar aspect of string cosmology and of the pre-big bang scenario [1, 10]. Light dilatons are particularly interesting, in this context, because if $m \lesssim 100$ Mev the dilatons of the background have not yet decayed, if $m \lesssim 10$ keV they could provide a significant contribution to the present cold dark-matter density, and if $m \lesssim 10^{-12}$ eV they are also in principle detectable [2, 3, 4] by "advanced" (i.e., second-generation) interferometers and by (future) resonant spheres (provide the mass is in the sensitivity band of the antennas). Spherical detectors, in particular, seem to be favoured with respect to interferometers if the non-relativistic dilaton spectrum is flat enough, and if it *is not* peaked at $p = m$. In any case, the search for cosmic dilatons (or, more generally, for relic scalar particles) may provide unique infomation on primordial cosmology and Planck-scale physics.

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References

[1] Gasperini M 1993 *Phys. Lett.* **B327** 314
Gasperini M and Veneziano G 1994 *Phys. Rev.* D **50** 2519

[2] Gasperini M 1999 *Phys. Lett.* **B470** 67

[3] Gasperini M 2000 *Phys. Lett.* **B477** 242
Gasperini M and Ungarelli C 2001 *Phys. Rev.* D **64** 064009

[4] Coccia E, Gasperini M and Ungarelli C 2002 *Phys. Rev.* D **65** 067101

[5] Witten E 1984 *Phys. Lett.* **B149** 351

[6] Witten E 1995 *Nucl. Phys.* **B443** 85

[7] Grishchuk L P 1975 *Sov. Phys.* JETP **40** 409
Starobinski A A 1979 JETP *Lett.* **30** 682

[8] Gasperini M and Veneziano G 1999 *Phys. Rev.* D **59** 43503

[9] Gasperini M 2000 *Proc. IX Marcel Grossman Meeting* (Rome, July 2000), eds. Gurzadyan V G *et al.* (World Scientific, Singapore), gr-qc/0009098.

[10] Gasperini M and Veneziano G 2003 *Phys. Rep.* **373** 1

[11] Fischbach E and Talmadge C 1992 *Nature* **356** 207

[12] Taylor T R and Veneziano G 1988 *Phys. Lett.* **B213** 459

[13] Hoyle C D *et al.* 2001 *Phys. Rev. Lett.* **86** 1418

[14] Damour T and Polyakov A M 1994 *Nucl. Phys.* **B423** 352

[15] Brustein R, Gasperini M and Veneziano G 1997 *Phys. Rev.* D **55** 3882

[16] Bianchi M *et al* 1998 *Phys. Rev.* D **57** 4525
Brunetti *et al* 1999 *Phys. Rev.* D **59** 44027
Maggiore M and Nicolis A 2000 *Phys. Rev.* D **62** 024004

[17] Allen B and Romano J D 1999 *Phys. Rev.* D **59** 102001