Gamma-ray bursts, axion emission and string theory dilaton

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Abstract

The emission of axions from supernovae is an interesting possibility to account for the Gamma-Ray Bursts provided their energy can be effectively converted into electromagnetic energy elsewhere. The connection between supernova and gamma-ray bursts has been recently confirmed by the observed correlation between the burst of April 25, 1998 and the supernova SN1998bw. We argue that the axion conversion into photons can be more efficient if one considers the coupling between an intermediate scale axion and the string theory dilaton along with the inclusion of string loops. We also discuss the way dilaton dynamics may allow for a more effective energy exchange with electromagnetic radiation in the expansion process of fireballs.

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1 Introduction

Gamma-Ray Bursts are certainly among the most striking astrophysical discoveries of the century. Ever since their fortuitous discovery in late sixties these flashes of gamma radiation have been the subject of great interest and debate. There has been more than 3000 bursts recorded, about 2100 of which by the Burst and Transient Source Experiment (BATSE) at NASA’s Compton Gamma-Ray Observatory and till February 1997 no observation of bursts counterparts in any other wavelength had ever been recorded, although some evidence for an afterglow emission was found in high energy gamma rays when GEV photons were detected about $5 \times 10^3$ seconds after the burst GRB 940217. Data from BATSE clearly indicate that the distribution of bursts is isotropic around us although not homogeneous in a 3-dimensional Euclidean space. This last feature, which arises from the lack of low intensity sources is, of course, a strong evidence for the cosmological nature of the bursts. This suspicion has been recently confirmed by the observations of the burst afterglows in the X-Ray region by BeppoSAX, a Dutch-Italian satellite, and in the optical for the burst of February 28th, 1997 (GRB 970228) and GRB 970508. For the latter an afterglow in the radio has also been detected. These observations made it possible to determine the afterglow’s redshift, for instance, $z = 0.835$ for GRB 970508. The identification of a host galaxy with $z = 3.42$ for the big burst of December 14, 1997 provides further confirmation that gamma-ray bursts are extragalactic in origin. Furthermore, the very recent observation that the supernova SN1998bw located in the spiral galaxy ESO 184 - G82 about 140 million light years away and the gamma-ray burst GRB980425 are related strongly suggests that at least some class of gamma-ray bursts have its origin in supernovae. Actually, Colgate has proposed the gamma-ray emission from supernovae as a possible origin of gamma-ray bursts more than twenty years ago, however it is only more recently that many of the theoretical problems ensued by this idea have been addressed.

The proposed models for explaining the GRBs observations require either quite
drastic phenomena involving merging of compact objects and ultra relativistic motion of the source or new physics. An example of the former is Paczyński’s hypernovae model which considers as a final result of some merging process a 10 $M_\odot$ Kerr black hole and the mechanism of Blandford-Znajek in order to obtain the extremely large magnetic fields, $B \sim 10^{15}$ G, required to match the observed energy of the bursts, $E_{\text{GRB}} \sim 10^{52}$ ergs. A quite interesting suggestion involving new physics assumes energy scapes from supernovae via the emission of axions and is converted into electromagnetic energy elsewhere [15]. This proposal solves the so-called compactness problem related with the quick thermalization of the electromagnetic energy that one expects in optically thick media due to Compton scattering with electron-positron pairs [16]. This is the usual situation one encounters in merging scenarios to explain gamma-ray bursts. Furthermore, one has also to consider that, in case the electromagnetic energy is contaminated by more than $10^{-5}$ $M_\odot$ of baryons then it is shown that the photon energy tends to degrade to lower energies implying that the burst duration will be stretched beyond the observation limits [17]. Neutron star merging scenarios involve, for instance, about $10^{-2}$ $M_\odot$ of baryonic debris [18]. Of course, these difficulties can be, at least in principle, overcome assuming the source of the bursts is accelerated to the ultra relativistic regime as can be achieved in fireballs created from the merging of compact objects (see for instance Refs. [19] for recent reviews). The non-thermal spectra of the gamma-ray bursts suggest a sudden energy release as encountered in some situations in cosmology such as for instance in bubble collisions in first order phase transitions or resonant decay of bosonic fields into radiation. A quick estimate however, shows that the simplest implementation of these ideas is irrelevant in the gamma-ray bursts problem. Indeed, consider for instance, that $\Omega_V < 0.5$ (which is supported by the most recent studies of the cosmological parameters [20]), then the available vacuum energy is about $\rho_V \sim 5 \times 10^{-6} h_0^2$ GeV cm$^{-3}$ ($h_0$ being the Hubble constant in units 100 km s$^{-1}$ Mpc$^{-1}$) which is just a tiny fraction, even when allowing for a large redshift factor, of the energy density in gamma-ray bursts assuming the bursts are cosmological and that their source is fairly compact $D_{\text{source}} < 3 \times 10^3$ km as can be estimated from smallest observed time variability interval $\Delta T < 10$ ms [21]. In this work we consider the proposal of Ref. [15] in the context of string theory.
As we discuss below, in string theories the well known cosmological upper bound for the vacuum expectation value for the breaking of the Peccei-Quinn symmetry, $f_{PQ} < 10^{12}\, GeV$, may not hold due to the presence of the moduli fields, which on its own prevents axions as being the putative source of the gamma-ray bursts if axions are allowed in Grand Unified Theories (GUTs), even though the inclusion of string loops may allow, under conditions, $f_{PQ} \approx \text{few} \, 10^{12}\, GeV$. These conclusions are, of course, strongly dependent on the estimates of the energy release of gamma-ray bursts and may be relaxed if $E_{GRB} < 10^{52}\, \text{ergs}$. We shall also point out that our scheme is compatible with the mini-supernova model of Ref. [22] provided the axion energy can be released nearby the exterior layers of red giants. It is worth stressing the naturalness of considering astrophysical and cosmological phenomena involving axions since these particles stand out as the most prominent candidates for the dark matter of the Universe in the much observationally favoured Cold Dark Matter Models. Finally, we shall see that independently of the presence of axions the dynamics of the string theory dilaton may play a role in the fireball expansion process.

2 Axion-Dilaton Coupling

Axions arise in particle physics to explain the strong CP problem via the Peccei-Quinn mechanism [23] (see eg. Ref. [24] for a review). Axions are pseudogoldstone bosons associated with the spontaneous breaking of an anomalous chiral $U(1)_{PQ}$ symmetry with vacuum expectation value, $f_{PQ}$. Axions acquire mass as QCD instantons break $U(1)_{PQ}$ and $m_a = \frac{f_a}{f_{PQ}} m_\pi$, where $f_\pi = 93\, MeV$ and $m_\pi = 134.5\, MeV$. For standard axions, bounds on $f_{PQ}$ can be obtained from astrophysical and cosmological considerations [24]:

$$10^9\, GeV < f_{PQ} < 10^{12}\, GeV,$$

(1)

where the lower bound arises from the demand that axions do not lead to a quick cooling of stars while the upper bound comes from requiring that the classical coherent oscillations of axions do not dominate the Universe dynamics at present [25]. In the context of string theory, however, the cosmological bound may not hold as moduli fields which are assumed to have masses comparable to the gravitino are substantially
heavier than the axions, implying that their coherent oscillations dominate the Universe dynamics quite early on \cite{26}. This may imply that the axion can be much more “invisible” than usually assumed and that axions arising from GUTs or supersymmetric GUTs via the breaking of R-type symmetries are cosmologically acceptable. The possibility that $f_{PQ}$ is greater than the intermediate scale $10^{12} \text{ GeV}$ renders axions unfeasible as candidates for solving the compactness problem of gamma-ray bursts if one assumes that the energy release of gamma-ray bursts is indeed $E_{GRB} \sim 10^{52} \text{ ergs}$. We shall see that this conclusion remains essentially unaltered if one considers the effect of string loops and assumes these can stabilize the dilaton in the absence of a potential \cite{27}. This is a quite relevant suggestion as moduli fields, including the dilaton, are shown to remain massless in all orders in string perturbation theory. Indeed, after assuming that the dilaton coupling is universal, the string dynamics at low energies compared with the Planck mass, $M_P$, is described by the following lowest order bosonic action involving axion, dilaton, gravity and Yang-Mills fields \cite{27}:

$$S_B = \int d^4x \sqrt{-g} \left\{ -\frac{R}{2k^2} + 2(\partial\phi)^2 + \frac{k_i}{4} B(\phi) F^a_{\mu\nu} F^{\mu\nu a} + \frac{b_i}{4} B(\phi)^3 \frac{a}{f_{PQ}} e^a_{\mu\nu} F^{\mu\nu a} + \ldots \right\},$$

where $k^2 = 8\pi M_P^{-2}$, $k_i$ and $b_i$ are order one constants, the field strength $F^a_{\mu\nu}$ corresponds to the one of a Yang-Mills theory with gauge group $G_i$ which is a subgroup of $E_8 \times E_8$ or $SO(32)$ and $\tilde{F}^{\mu\nu}$ is the dual of the gauge field strength; moreover, following Ref. \cite{27}, we introduce the universal function of the dilaton, $\phi$:

$$B(\phi) = e^{-2k\phi} + c_0 + c_1 e^{2k\phi} + c_2 e^{4k\phi} + \ldots,$$

which expresses the fact that string-loop interactions have an expansion in powers of the dilaton, that is $g_S \equiv e^{2k\phi}$; the coefficients $c_0, c_1, c_2, \ldots$ are presently unknown. As discussed in \cite{27}, when accounting for string loops the dynamics of the dilaton is such that the function $B(\phi)$ must reach a maximum at present, when say $\phi = \phi_0$, as fermion masses are shown to be proportional to inverse powers of $B(\phi)$. The gauge coupling constants are extracted from the dilaton-gauge field coupling $\frac{k_i}{4} B(\phi) \text{Tr}(F^a_{\mu\nu} F^{\mu\nu a})$ in the bosonic action, from which follows that $g_i^{-2} = k_i B(\phi_0)$. Of course, the coupling between the axion and the electromagnetic field, i.e. $-\frac{\alpha_{EM}}{2} \alpha_{EM} B(\phi)^4 \frac{a}{f_{PQ}} \mathbf{E} \cdot \mathbf{B}$,
is contained in the third term in (2) for the $U_{EM}(1)$ subgroup of $G$ such that $c_{a\gamma\gamma}$ hides all the gauge symmetry branching from the GUT gauge group down to $U_{EM}(1)$. For the simplest case $c_{a\gamma\gamma} = 8\pi^2 k_i b_i$. Notice that we have not included the function $B(\phi)$ in the definition of $c_{a\gamma\gamma}$. Given the universality of the dilaton coupling, the quark sector has a generic term $\frac{c_{aPQ} B(\phi)}{2\sqrt{f_{PQ}}} \bar{\psi}\gamma^\mu\gamma^\beta\gamma^\delta\gamma\bar{\psi} \partial^\mu a$ [28]. The coupling between the axion and the gauge field ensures the photon conversion of axions due to magnetic fields surrounding the progenitor neutron star or interstellar medium. The conversion of axions (and also omions, the Nambu-Goldstone bosons outside the core of global cosmic strings) into photons has been discussed in Refs. [29] with the conclusion that strong inhomogeneous magnetic fields are required and that the conversion probability is proportional $|B|^2$ and is suppressed by a factor $(\omega_{pl}^2 - m_a^2)^{-1/2}$ where $B$ is the magnetic field and $\omega_{pl}$ the plasma frequency which is an effective mass for the photon. Of course, the conversion of axions is greatly enhanced if $\omega_{pl} \approx m_a$. We can hence conclude that an efficient conversion of axions into photons requires strong inhomogeneous magnetic fields and media where the plasma frequency is close to the axion mass. The difficulty in meeting the conditions for efficient conversion into photons may be at the origin of the difference of rates between supernova and gamma-ray bursts.

For $m_a < 10^{-2}$ eV axions free stream through neutron stars with temperature $T_{NS}$ leading, for standard axions, to a total luminosity given by [28]:

$$L_a \approx 2 \times 10^{50} \times 10^{\pm 1.5} \left( \frac{m_a}{10^{-4}\text{ eV}} \right)^2 \left( \frac{T_{NS}}{30\text{ MeV}} \right)^{3.5} \text{ erg s}^{-1}. \quad (4)$$

This luminosity is on its own inconsistent, for $m_a \approx 10^{-4}$ eV, with the best-fit gamma-ray burst standard candle luminosity, $L_{GRB} \sim 1.6 \times 10^{52} \text{ erg s}^{-1}$, for $\Omega = 1$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [30] and the possibility of absence in string theory of an upper bound for $f_{PQ}$ makes things worse as axions may be even lighter than $10^{-5}$ eV. The inclusion of string loops alters slightly this as one should then multiply the luminosity (eq. (4)) by a factor $B(\phi_0)^2$ and $k_i B(\phi_0) \sim 10$. Thus, $L_{GRB} \approx 10^{52} \text{ erg s}^{-1}$ can be obtained for $f_{PQ} \approx 10^{11} \text{ GeV}$. Notice that, for instance, the SN1998bw explosion can be modelled by a spherically symmetric explosion of a quite massive star with a total ejected mass of about $10 M_\odot$ and approximately $3 \times 10^{52} \text{ ergs}$ of kinetic energy [11].
although it has been argued that energy releases of this magnitude actually reflect collimation effects and Doppler boosting [31]. This collimation implies that the energy output of gamma-ray bursts may be actually much smaller, $E_{GRB} \sim 10^{46} - 10^{48} \text{ergs}$, and suggests a higher rate of bursts possibly consistent with the supernovae rate [31, 32]. Energy considerations can also be relaxed if one considers the mini-supernova model proposed by Blinnikov and Postnov [22] in which an optical afterglow can be produced by the release of about $10^{50} \text{ergs}$ nearby the exterior $10^{-3} M_\odot$ layers of a red giant. This energy can be achieved by the emission of axions by supernovae and their conversion into radiation due to the strong magnetic fields in the outer layers of the red giant provided that $f_{PQ} \approx 10^{12} \text{GeV}$ if string loops are taken into account. Hence, we see that string loop effects can help the case of standard axions as mediators of the supernova burst energy, but on no ways they can save the case of axions arising from GUTs, unless the energy release of GRBs is much smaller than $10^{52} \text{ergs}$.

3 Fireball Expansion

Another way the dilaton may play a role is in the fireball expansion after the merging of compact objects, specially if one assumes, as suggested from the observation of GRB970228, GRB970508, GRB970828 and GRB971214, that the bursts afterglows are close to star forming regions with rather high redshifts, say $z \gtrsim 1$ [33]. Supposing that the expansion of the fireball and the ensued cooling is adiabatic, then the process can be described through the Milne cosmological model [34]. If one further assumes the radiation corresponds, for simplicity, to a triplet of massive vector fields with an $SO_I(3)$ internal global symmetry [35], it follows that one can build an homogeneous and isotropic model and show that the dilaton energy can be transferred into radiation as far as $B(\phi) > 0$ and its derivative with respect to $\phi$ is negative. This energy transfer has been previously discussed in the cosmological setting related with the so-called Polonyi problem [36] for the case of an $SO(3)$ gauge field [37].

Indeed, considering only homogeneous and isotropic field configurations on a spatially flat spacetime, the most general metric is given in terms of the lapse function,
\[ ds^2 = -N^2(t)dt^2 + R^2(t)d\Omega_3^2. \] (5)

We consider for simplicity a triplet of massive vector fields with an \( SO_I(3) \) global symmetry, our conclusions however, are qualitatively independent of this choice. We then use the following homogeneous and isotropic Ansatz for the vector field [35]:

\[ A_0 = 0 \quad ; \quad A_i(t)dx^i = 3\sum_{i=1}^{3} \chi_0(t)L_idx^i \] (6)

\( \chi_0(t) \) being an arbitrary function of time and \( L_i \) the generators of \( SO_I(3) \).

We start by dimensionally reducing action (2), allowing only for homogeneous and isotropic field configurations and dropping the axion term. This procedure allows treating the contribution of the vector fields on the same footing as the remaining fields, as opposed to the usual treatment of radiation as a fluid.

Introducing the Ansätze (5) and (6) into the action (2) leads after introducing a mass term for the vector field to the following effective action for the dilaton-Einstein-Proca system after integration over \( \mathbb{R}^3 \) and division by the infinite volume of its orbits:

\[ S_{\text{eff}} = -\int_{t_1}^{t_2} dt \left\{ -\frac{3\dot{R}^2R}{k^2N} + \frac{3R}{N}B(\phi) \left[ \frac{\chi_0^2}{2} - N^2m^2\chi_0^2 - \frac{N^2\chi_0^4}{R^28} \right] + \frac{2R^3}{N}\dot{\phi}^2 \right\}, \] (7)

where the dots denote time derivatives and \( m \) the mass of the vector fields. The equations of motion in the N=1 gauge are given by:

\[ 2\frac{\dddot{R}}{\dot{R}} + H^2 + \frac{k^2}{3}B(\phi)\rho_{\chi_0} + 2k^2\dot{\phi}^2 = 0, \] (8)

\[ \ddot{\phi} + 3H\dot{\phi} - \frac{1}{4}B'(\phi)\zeta_{\chi_0} = 0 \] (9)

\[ \ddot{\chi}_0 + \left[ H + \frac{B'(\phi)}{B(\phi)}\dot{\phi} \right]\ddot{\chi}_0 + 2m^2\chi_0 + \frac{\chi_0^3}{2R^2} = 0, \] (10)

where the primes denote derivatives with respect to \( \phi \), \( H = \dot{R}/R \) is the fireball rate of expansion, \( \rho_{\chi_0} = 3 \left[ \frac{\chi_0^2}{2R^2} + \frac{m^2\chi_0^2}{R^2} + \frac{\chi_0^4}{8R^4} \right] \) and \( \zeta_{\chi_0} = 3 \left[ \frac{\chi_0^3}{2R^2} - \frac{m^2\chi_0^2}{R^2} - \frac{\chi_0^4}{8R^4} \right] \).
Furthermore, the Friedmann equation is obtained extremizing the effective action (7) with respect to the lapse function:

$$H^2 = \frac{k^2}{3} \left[4\rho_\phi + B(\phi)\rho_\chi_0\right],$$

(11)

where $\rho_\phi = \frac{1}{2}\dot{\phi}^2$.

Our field treatment of radiation reveals an energy exchange mechanism that may turn out to be relevant in the process of expansion of the fireball. Working out the equations above, we obtain the energy exchange equations:

$$\dot{\rho}_\phi = -3H\dot{\phi}^2 + \frac{1}{4}B'(\phi)\zeta_{\chi_0}\dot{\phi},$$

(12)

$$\dot{\rho}_{\chi_0} = -4H\rho_{\chi_0} - \frac{3}{B(\phi)}\frac{B'(\phi)}{R^2}\dot{\phi}^2,$$

(13)

The new feature in these equations are the terms proportional to $\dot{\phi}$. If gamma-ray bursts are prone to occur in star forming regions with rather high redshifts, then the dynamics of the dilaton field may be relevant. Indeed, if $B(\phi) > 0$ and its derivative with respect to $\phi$ is negative then we see that radiation acquires the energy lost by the dilaton despite losses due to the fireball expansion depicted by terms proportional to $H$. Naturally, the energy exchange becomes less and less efficient as the fireball expands and it occurs predominantly when $H \approx \frac{B'(\phi)}{B(\phi)}\dot{\phi} \approx m$. This situation is similar to the one encountered in cosmology after inflation but prior the reheating phase [36].

Of course, as the photon in a plasma medium behaves as if having a mass $\omega_{pl}$, then we can identify our triplet of massive vector fields with the electromagnetic field and therefore $m = \omega_{pl}$. For small $\omega_{pl}$ and $\dot{\phi}$ our mechanism remains effective for quite a long time, provided the discussed conditions for $B(\phi)$ are satisfied. Even considering that, at a fundamental level, the electromagnetic radiation cannot be treated, due to its lack of rotational symmetry, as performed above, the basic features of the energy exchange mechanism are still present. This can be seen from the energy-momentum conservation equation

$$T^{EM}_{\mu\nu;\mu} = -B(\phi)^{-1}\left[T^\phi_{\mu\nu;\mu} + B(\phi)\rho_{\mu\nu}T^{EM}_{\mu\nu}\right],$$

(14)
which shows that a liquid transfer of dilaton energy into radiation may occur if $B(\phi)_{,\mu} < 0$. Nevertheless, it is worth emphasizing that our treatment of radiation as a triplet of massive vector fields seems to be more appropriate in capturing the main features of the energy exchange between fields in a medium.

4 Discussion and Conclusions

Gamma-ray bursts may possibly be the sole astrophysical evidence we have encountered so far suggesting new physics beyond the standard model. In this respect, massive objects of pure quark matter [38], quantum gravity effects in the propagation of electromagnetic waves in vacuo [39], neutron star explosion caused by accumulation of Q-balls [40], to mention just a few have been suggested in connection with these bursts. In any case, gamma-ray bursts are striking phenomena requiring extreme astrophysical conditions. In this work we have argued that axions emitted from supernovae, as suggested in [15], can be a potential explanation for the origin of the gamma-ray bursts. This possibility, although far from being proven, has gained support from the identification of the supernova SN1988bw as the source of the burst GRB980425. We have shown that, in the context of string theory, string loops may play a role in achieving the axion energy required to match the observations, for $f_{PQ} \lesssim 10^{11} \text{ GeV}$ if $E_{\text{GRB}} \sim 10^{52} \text{ ergs}$. For $f_{PQ} \approx 10^{12} \text{ GeV}$ we envisage that only via the presence of red giants afterglows can be explained, as suggested in [22]. This points to a distinct observational signature, namely the association of afterglows with supernovae and red giants. The large magnetic fields present in the outer layers of red giants may quite possibly be effective in the conversion into radiation of the energy from supernovae carried away by axions. Difficulty in satisfying the resonance condition, $\omega_{pl} \approx m_a$, and the small probability of association between supernovae and nearby red giants arise as an elegant explanation for the different rates of supernovae and gamma-ray bursts. In this context, one could also consider the possibility that the dilaton may acquire a potential (and hence a mass) non-perturbatively, as usually discussed, via the process of condensation of gauginos. Thus, a possible scenario would be accounting for the disruption of red giants outer layers due to the dilaton decay.
For that, one should require as a necessary condition that the dilatons would live at least as long as about the age of the Universe, that is $\tau_\phi \equiv \Gamma_\phi^{-1} = M_P^2/8\pi m_\phi^3 \approx 10^{17}$ s, from which follows that $m_\phi \sim 25$ eV. Notice that for this purpose the radiative decay of the axion is totally irrelevant as its lifetime is about $10^{45} \left(m_a/10^{-4} \ eV\right)^{-5}$ s.

Finally, we have shown that independently of the presence of axions, the dilaton dynamics may itself be relevant in the fireball expansion process in scenarios involving merging of compact objects and we have set, through the analysis of the energy exchange between the dilaton and a triplet of massive vector fields in an homogeneous, isotropic and adiabatic model, the conditions under which this dynamics is important, namely when $B(\phi) > 0$ and $B(\phi)_{,\mu} < 0$. 
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