Are Bulk Axions in Models with Extra, Large, Compact Dimensions Observable?

Shmuel Nussinov

School of Physics and Astronomy, Tel Aviv University
Ramat-Aviv, Tel Aviv 69978, Israel

(Dated: June 21, 2004)

Abstract

The high degeneracy of KK modes in models which have bulk axions moving in some extra, compact dimensions which are larger than O (Angstrom) strongly tightens the supernova upper bounds on the axion photon coupling making axions practically unobservable. Conversely, discovering axions directly or indirectly will exclude such models. These drastic conclusions are avoided if the supernova and bounds from solar axion searches are relaxed.

PACS numbers:
While axions have not been discovered to date they hold the fascination of a broad scientific community in approximately 30 years since the original suggestion.

Axions were motivated by particle physics. A new symmetry and attendant fields were introduced in order to dynamically relax to zero the $\theta$ parameter in the otherwise dangerous parity violation: $\theta E(c)B(c)$ term in the QCD langrangian. The axion emerged as the light “pseudo” Goldstone boson in the spontaneous breaking of this (Peccei-Quinn) symmetry. Despite many efforts no alternative explanation of the experimentally tiny $\theta$ was found. Axions are of much interest in astrophysics as coherent, cold, dark matter and possibly manifest in hot, dense environments and/or strong magnetic fields.

A key role is played by the axion two-photon coupling:

$$g(a, \gamma, \gamma) \cdot E(\text{em}) \cdot B(\text{em})$$

which generates spontaneous $a \rightarrow 2\gamma$ decays, coherent $a \rightarrow \gamma$ transitions in strong $E$ or $B$ fields, and contributes, via virtual $\gamma \rightarrow$ axion $\rightarrow \gamma$ transition, to vacuum bifringing of polarized light in strong $B$ fields. Astrophysical considerations, alongside experimental searches, limit the allowed axion mass $m$ and coupling. In particular, the (conservative!) limit:

$$M = g(a, \gamma, \gamma)^{-1} > 10^{10}\text{GeV}$$

is required to avoid catastrophic cooling via (volume) emission of axions—from red giants and in supernovae collapse.

In supersymmetric/string theories the scalar “dilaton” field fixing the gauge coupling $g$ is a natural chiral partner of the pseudoscalar axion associated with varying $\Theta$. It is therefore natural—in theories with $n$, large, compact, extra dimensions (LCED) to have (i) both axion and dilaton on the thin “Brane”, along with the standard model particle, or (ii) both in the “Bulk”. The possible connection of dilatons with bulk gravity favors option (ii).

In the following we will assume that axions are bulk fields in some LCED model. Details of the model beyond the dimensionality, $n$, of the extra space where the axions live and its scale $R$ are irrelevant to our discussion.

The possible states of bulk axions correspond to an $n$ dimensional lattice of Kaluza-Klein
“momenta”:

\( (k_1, k_2, \ldots, k_n), \quad k_i = \ell_i/R \) \hspace{1cm} (3)

\( \ell_i = 0 \) or integer. These states have masses:

\[
m(KK(\ell_1, \ell_2 \ldots \ell_n)) = (1/R) \cdot \sqrt{\ell_1^2 + \ell_2^2 + \ldots + \ell_n^2}
\] \hspace{1cm} (4)

The number:

\[
N(KK)(T(a)) \sim (R \cdot T(a))^n
\] \hspace{1cm} (5)

of KK axionic states with mass \( m(KK) < T(a) \), which can be excited in hot environments of temperature \( T(a) \), can be very large, and enhanced emission of axions from the sun has been considered.\(^2\)

For a given \( g(a, \gamma, \gamma) = M^{-1} \), axion emission is enhanced in theories with LCED by the above large number of KK species: \( EF(a) \sim (RT(a))^n \). For \( n = 2 \) and \( R = eV^{-1} \), the values in Ref.\(^2\), the enhancement factor \( EF \) in the sun with \( T(\text{core}(\odot)) \sim T(\text{sun}) \sim 1.4 \text{KeV} \) is:

\[
EF(\text{sun}) \sim (T(\text{sun}) \cdot R)^n \sim 2 \cdot 10^6.
\] \hspace{1cm} (6)

Unfortunately LCED scenarios with bulk axions drastically suppress solar axion emission and even more so the number of detected axions. If solar (or any!) axions are ever detected, most LCED models are ruled out.

The argument is simple and is implicit in some early papers.\(^3\) While axions from the nearby sun are expected to dominate axions from other astrophysical sources like red giants and supernovae cores, the latter are \( \sim 10 \) and \( 10^4 \) hotter than the stellar core, respectively. Thus the enhancement factor in supernovae is much larger than in the sun.

\[
EF(\text{supernova}) = (T(\text{supernova}) \cdot R)^n = 10^{4n} \cdot EF(\text{sun})
\] \hspace{1cm} (7)

Next recall that the lower bound on \( M \) of Eq. \(^2\) was derived by demanding that the axionic luminosity (scaling like \( M^{-2} \)) in the standard single light axion scenario be less than the total luminosity of the collapsing core. To ensure this in the present scenario we need to compensate \( EF(\text{supernova}) \) by increasing \( M^2 \) by \( EF(\text{supernova}) = (T(\text{supernova}) \cdot R)^n \). Hence, in models with bulk axions in LECD the bound on the axion electromagnetic coupling is much stronger than that of Eq. \(^2\):

\[
\text{new (LCED) bound on } M = \text{old bound on } M \cdot (T(\text{supernova}) \cdot R)^{n/2}
\] \hspace{1cm} (8)
Recalling Eq. (6) we find that relative to standard single axion scenarios the number of detected solar axions, which is proportional to $M^{-4}$, is reduced by

$$(T(\text{supernova}) \cdot R)^{2n}/(T(\text{sun}) \cdot R)^n.$$  \hspace{1cm} (9)

The parameters of Eq. (6) and $T(\text{supernova}) \sim 10$ MeV then imply a $\sim 10^{22}$ reduction!

Axion effects in pure terrestrial laboratory experiments—say, by contributing to vacuum birefringence of laser light (PVLAS)—are also strongly suppressed in LCED models with bulk axions relative to the ordinary one axion scenario.

The “ellipticity” angle $\Psi$ which would be generated in the PVLAS experiment with one axion of mass $m$ and electromagnetic coupling, $M^{-1}$, is given by

$$\Psi \sim (BL/M)^2 \cdot (E(\gamma)/L \cdot m^2)$$  \hspace{1cm} (10)

where $B$ is the strong magnetic field applied and $L$ is the distance along which the initial linearly polarized laser light has accumulated the ellipticity. Strictly the last equation applies only in the regime $m(\text{axion}) < E(\gamma)$. Other intermediate states, such as $e^+(e^-)$ pairs in QED and heavier axions also contribute but along shorter coherence lengths and much less efficiently.

In the LCED scenario we could have, when $\lambda(\gamma) < R$, many, $\sim (E(\gamma) \cdot R)^n$, axions with masses smaller than $E(\gamma)$. The ellipticity contributed by each of these axion KK models adds up coherently and, hence, the effect is enhanced by this factor.

However, again, as in the previous cases, the supernova bound reverses the conclusions. Any putative $(E(\gamma) \cdot R)^n$ enhancement is vitiated by the much more drastic decrease (by $(T(\text{SN}) \cdot R)^n$) of the $M^{-2}$ factor in Eq. (10) required in order to satisfy the supernova cooling bound. This yields a net suppression by $(T(\text{SN})/E(\gamma))^n \sim 10^{8n}$, with $T(\text{SN}) \sim 10$ MeV and $E(\gamma) \sim 0.1$ eV.

All the above suppressions are avoided if $R < 1/T(\text{supernova}) \sim 20$ Fermi. The lightest KK excitation is then heavier than 10-30 MeV, making the LCED models irrelevant for astrophysical axions and vice versa astrophysical considerations limit axion physics in the same old way as in the ordinary four-dimensional models.
The supernova bounds on $M$ could conceivably be relaxed by having quick axion $\rightarrow$ photon conversion in the strong magnetic fields. This would be resonantly enhanced by axion plasmon degeneracy. This conversion may be modified and potentially accelerated if as in a recently modified LCED scenario where KK momentum conservation in the bulk is relaxed allowing for decays of heavier KK axions into lighter ones.

We conclude with a few comments:

(i) The above phenomenological, simplistic discussion suggests that bulk axions, if allowed to move in the same extra dimensions as originally conceived for gravity, are constrained (by the supernova cooling bound) to have an extremely small coupling to photons. At a slightly deeper theoretical level such tiny couplings and $M \sim M(\text{Planck}) \sim 10^{19}$ Gev is expected: the same “dilution” by bulk to brane volume ratio suppresses both axion and graviton couplings. Indeed, supernovae were used also to limit directly models LCED and many gravitational KK excitations.

(ii) Consider axions of mass $m$. If the axions’ mass, $m \sim T(a)$, a fraction $F(b) \sim (V(\text{escape}(a))/c)^3$ of the axions, namely, those emitted with velocities smaller than the escape velocity, will gravitationally bind to the star in question. For the sun ($V(\text{escape}) \sim 560 \text{ km/sec}$) and $m(\text{axion}) \sim 5 \text{ KeV}$, this fraction is $10^{-7}$.\footnote{\text{[9], [10]}} If the lifetime for $a \rightarrow \gamma + \gamma$ $t$ (axion) $\sim m^{-3}$ can be as short as $10^{20}$ seconds for $m \sim 10$ KeV, and if further solar axion luminosity was a $\sim$ few percent of the total solar luminosity, then radiative decays of the bound solar axions could generate the x-rays observed from the quiescent sun and resolve other longstanding puzzles. One axion-like particle with the desired mass and coupling yields an x-ray sharply peaked at one energy ($E \sim m/2$) — contrary to observation — and a framework with many axions is required.

(iii) More massive $m \sim 10$ MeV axion-like particles can be emitted from supernova cores. If it radiatively decays during times shorter than hubble time, then the bound on diffuse
∼ 10 MeV “relic” gammas from all past supernovae implies that only a small fraction $f \sim 10^{-5} - 10^{-6}$ of the supernova energy can then be emitted via such axions. Since the photon flux scales as $M^{-4}$ this improves the ordinary supernova bound on $M$ by $f^{-(1/4)} \sim 20-30$.

(iv) The original observation by DiLella and Zioutas\cite{9} that some massive KK axions are gravitationally captured, applies to neutron stars. Using Eq. (11) and $V(\text{escape})(\text{SN})/c \sim 1/3$, we find that ∼ 5% of all axions with mass $m \sim T(\text{SN}) \sim 10\text{-}30$ MeV will be gravitationally trapped. The bound of Eq. (8) allows axions to carry 1/2 of the ∼ 3-4 $10^{53}$ ergs collapse energy. The total energy/mass of the captured axions is: $10^{51}$ ergs/10$^{30}$ grams. The radiative decays of such axions yield ∼ 10 MeV gammas with a luminosity

$$L(\gamma, \text{bound axions}) \sim 10^5/t(\text{decay})(\text{ergs/sec})$$

(12)

About 1/4 of the gammas hit the surface and could make old neutron stars shine with high surface temperatures.

Using $m = m(\text{axion}) = 30$ MeV we find\cite{2} $t(\text{decay}) \sim 64\pi \cdot M^2/m^3 \sim (M/30\text{MeV})^2 \cdot 10^{-20}$ sec. which, with the minimal $M$ in Eq. (2) (10$^{10}$ GeV) and corresponding bound (8), yields: $t(\text{decay}) \sim (R \cdot 30 \text{ MeV})^n \cdot 10^3$ sec. For the parameters used above ($R \sim \text{eV}^{-1}$ and $n = 2$) we find $t(\text{decay}) \sim 10^{18}$ sec. The resulting luminosity in Eq. (12), ∼ 10% $L(\text{solar})$ leads to observable radiation from old neutron stars. The above effect scales as ∼ $M^{-4}$. Thus using $M \sim 10^{12}$ GeV—just 100 times the most conservative lower bound—completely evades it.

(v) A more subtle and possibly dramatic effect discussed context of halo particles\cite{11,12} is the migration of the accumulated particles to the center of the star. The latter then form a “mini black hole” which, in turn, “gobbles up” the whole star into a bigger black hole!

The bosonic axions cannot sustain the strong gravity of the very dense ($\rho \sim 10^{15}$ gr/cm$^3$) core by Fermi-pressure. However, the predominant axionic interactions with matter are not elastic but rather axionic Compton or Primakoff effects. Rather than lose energy via multiple elastic collisions, the axions convert into photons and get absorbed preempting the black hole scenario. Rather the absorbed axions contribute to the heating up of the old, cold neutron just like the neutron star halo axions’ spontaneous radiative decay discussed above.
Acknowledgement

I am much indebted to Konstantin Zioutas for many helpful discussions. This particular note was motivated by his works with Di Lella and my interest in recent years in solar axions by his suggestions at the early stages of the Solax and Cast experiments.

* Electronic address: nussinov@post.tau.ac.il

[1] G. G. Raffelt, Ann. Rev. Nucl. Part. Sci. 49, 163 (1999), hep-ph/9903472.
[2] L. Di Lella, A. Pilaftsis, G. Raffelt, K. Zioutas, Phys. Rev. D 62, 125011 (2000) hep-ph/0006327.
[3] S. Chang, S. Tazawa and M. Yamaguchi, hep-ph/9900240 (1999) and hep-ph/9912455 (1999).
[4] PVLAS Experiment: Ferrara-Legnaro-Pisa-Trieste-Udine collaboration at the INFN Legnaro National Lab, see Brandi et al., NIM A 329, 461 (2001).
[5] L. Maiani, Q. Petronzio and E. Zavattini, Phys. Lett. B 175, 359 (1966).
[6] R. Mohapatra, S. Nussinov and A. Perez-Lorenzana, Phys. Rev. D 68, 116001 (2003) hep-ph/0308051.
[7] S. Hannestad and G. G. Raffelt, Phys. Rev. D 67, 125008 (2003), [Erratum-ibid. D 69, 029901 (2004)], arXiv:hep-ph/0304029.
[8] K. R. Dienes, E. Dudas and T. Gherghetta, arXiv:hep-ph/9912455 (Dec. 1999).
[9] L. Di Lella and K. Zioutas, Astropart. Phys. 19, 145 (2003), astro-ph/0207073.
[10] K. Zioutas, K. Dennerl, L. DiLella, D.H.H. Hoffmann, J. Jacoby, Th. Papaevangelou, Astrophys. J. 607, 575 (2004), astro-ph/0403176.
[11] I. Goldman and S. Nussinov, Phys Rev D 40 3221 (1979).
[12] A. Gould, B. T. Draine, R. W. Rumanai and S. Nussinov, Phys. Lett. B 238, 337 (1990).