Hints of a Cosmic Axion Background

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In models of particle physics and cosmology arising from compactifications of string theory, the reheating of the standard model after inflation generically proceeds through the decay of heavy moduli. Non-vanishing branching ratios for moduli decay into axions generate axionic dark radiation which linger in the present universe as a homogeneous and isotropic background of relativistic axions, hence called the Cosmic Axion Background (CAB). Axion-photon conversion in magnetic fields may render the CAB visible, and we show that the soft X-ray excess observed in galaxy clusters may provide hints for the existence of a CAB.

1 Reheating in String Theory

A salient feature of the four-dimensional effective theories arising from compactifications of string theory is the presence of scalar particles with feeble, Planck-mass suppressed interactions. Such particles, or moduli, parametrize the size and shape of the compactification manifold and determine the values of coupling constants in the four-dimensional effective theory. The scalar potential for the moduli may arise from both perturbative and non-perturbative effects, and to extract predictions from the theory, this potential must be minimised and meta-stable vacua within the regime of computational control identified.

Over the past decade a number of relatively general methods to obtain controlled compactifications have been found and investigated by many authors, see e.g. [1, 2, 3] for compactifications of type IIB, and [4] for G_2 compactifications of M-theory. For compactifications with soft supersymmetry breaking at the TeV-scale, the lightest moduli turn out to have a mass of $m_\Phi \approx 10^6$ GeV in several moduli stabilisation scenarios [5, 6, 7].

Moreover, successful string theory models of our universe must in addition to stabilising moduli also realise realistic particle phenomenology and provide a compelling cosmology, which is typically assumed to include a period of inflation in the early universe. String theory models of inflation generically lead to the displacement of moduli from their final meta-stable minimum, and hence to oscillating moduli at the end of inflation. An oscillating scalar field red-shifts like matter,

$$\rho_{\text{moduli}} \sim 1/a(t)^3 \,,$$

where $a(t)$ denotes the Friedmann-Robertson-Walker scale factor. Thus, with time the oscillating moduli field will come to dominate over any initial radiation, which red-shifts like $\rho_{\text{radiation}} \sim 1/a(t)^4$.

The massive moduli fields decay with a typical life-time of

$$\tau \sim 8\pi \frac{M_{Pl}^2}{m_\Phi^3} \approx 10^{-4}\ \text{s} \left(\frac{10^6\ \text{GeV}}{m_\Phi}\right)^3 ,$$

where m_Φ denotes the modulus mass and M_{Pl} denotes the reduced Planck mass. The decay of the lightest moduli fields into visible sector particles will reheat the Standard Model to a temperature,

$$T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_{Pl}^{1/2}} \sim 0.6\ \text{GeV} \left(\frac{m_\Phi}{10^6\ \text{GeV}}\right)^{3/2} .$$

2 Axionic dark radiation from moduli decay

String compactifications typically give rise to additional light hidden sectors to which the moduli may couple with M_{Pl} suppressed couplings. We here consider the theoretically well-motivated case in which the moduli has an additional decay channel into axion-like particles (hence, axions). Such a decay channel may arise from a Lagrangian coupling,

$$\mathcal{L} \supset \frac{1}{2} \frac{\Phi}{M_{Pl}} \partial_\mu a \partial^\mu a \,,$$

and gives rise to axions with energy $E_a^{(0)} = m_\Phi/2 \approx (M_{Pl}/m_\Phi)^{1/2} T_{reheat} \gg T_{reheat}$ [9, 10]. These axions contribute to the *dark radiation* of the universe, and affect the CMB spectrum and the BBN abundances through the corresponding increase in the Hubble expansion parameter. The amount of dark radiation is traditionally parametrized in terms of the "effective number of neutrino species", $N_{eff} = 3.046 + \Delta N_{eff}$. For axionic dark radiation arising from the decay $\Phi \to aa$, ΔN_{eff} is given by

$$\Delta N_{eff} = \frac{43}{7} \frac{B_a}{1 - B_a} \left(\frac{g_\star(T_{\nu\ decoupling})}{g_\star(T_{reheat})}\right)^{1/3} ,$$

where B_a denotes the branching ratio into axions, and $g_\star(T)$ denotes the number of degrees of freedom in thermal equilibrium at temperature T.

There are tentative observational hints of dark radiation at the $1 - 2\ \sigma$ level both from the determination of light element abundances at BBN and from observations of the CMB, as summarised in table 1. Closely following [8], in this contribution to the *Proceedings of the 9th Patras Workshop on Axions, WIMPs and WISPs*, we will entertain the possibility of axionic dark radiation contributing to the energy density of the universe.

Experiment	N_{eff}
CMB: WMAP9 [11]	3.55 ± 0.60
CMB: Planck [12]	3.30 ± 0.27
CMB+H_0: WMAP9 +H_0 [11]	3.89 ± 0.40
CMB+H_0: Planck +H_0 [12]	3.62 ± 0.25
BBN+CMB: Cook *et al.* [13]	3.28 ± 0.28
BBN: Cook *et al.* [13]	3.57 ± 0.18

Table 1: Observational hints of dark radiation.

2.1 The Cosmic Axion Background

As the universe expands, the axion energies redshift as $E_a(t) = E_a^{(0)} a(t_0)/a(t)$ where $a(t_0)$ denotes scale factor at the time of decay. In the approximation in which all moduli decay simultaneously at $t_0 = \tau$, this results in a mono-energetic population of relativistic axions which will remain a factor of approximately $(M_{Pl}/m_\Phi)^{1/2}$ more energetic than the visible sector radiation (up to small changes in $g_\star$). In reality however, moduli decaying early will result in axions which appear more red-shifted than those arising from subsequent moduli decays, and in [14], the non-thermal spectrum of the present day axions was calculated. For $m_\Phi = 10^6$ GeV, the resulting axion spectrum in our present universe has a mean energy of around $E_a^{(today)} \approx 200$ eV, and is shown in Figure 1. These axions constitute a homogenous and isotropic Cosmic Axion Background (CAB) with a present day number density of $n_a^{(today)} \approx 7 \cdot 10^{-5}$ cm^{-3} and a flux of $\Phi_a^{(today)} \approx 5 \cdot 10^5$ cm^{-2} s^{-1}.

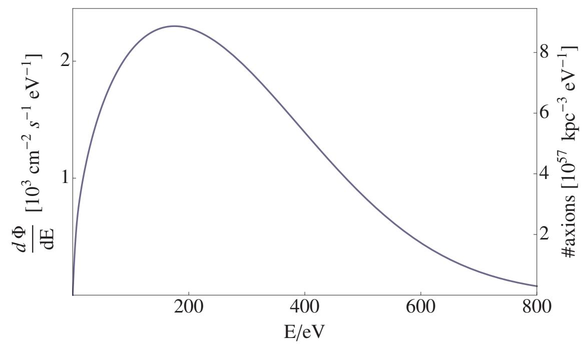

Figure 1: The present day CAB spectrum arising from decay of a modulus with $m_\Phi \sim 10^6$ GeV.

3 Hints of a Cosmic Axion Background

It has long been realised that axions may convert into photons in the presence of a magnetic field [15, 16]. The axion-photon Lagrangian is given by

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{a}{4M} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 \,,$$

where bounds from supernova constrain $M > 10^{11}$ GeV, and we will here consider an axion-like particle with $m_a^2 \approx 0$. The probability for an axion traveling through a perpendicular magnetic field with coherence length L and field strength B to convert into a photon is given by [17],

$$P(a \to \gamma) = \sin^2(2\theta) \sin^2\left(\frac{\Delta}{\cos 2\theta}\right) \,,$$

where $\tan 2\theta = \frac{2B\omega}{M m_{eff}^2}$, $\Delta = \frac{m_{eff}^2 L}{4\omega}$, $m_{eff}^2 = m_a^2 - \omega_{pl}^2$, ω_{pl} is the plasma frequency,

$$\omega_{pl} = \left(4\pi\alpha \frac{n_e}{m_e}\right)^{1/2} = 1.2 \cdot 10^{-12} \sqrt{\frac{n_e}{10^{-3}\text{cm}^{-3}}} \text{ eV} \,,$$

and ω denotes the photon energy. Though not crucial for our analysis, we note that in the small-angle approximation $\theta \ll 1$ and $\Delta \ll 1$, the conversion probability is simply given by

$$P(a \to \gamma) \approx \frac{1}{4} \left(\frac{BL}{M}\right)^2 .$$

Thus, a CAB may possibly be detectable as photons in the extreme ultraviolet (EUV) or soft X-ray spectrum through conversion in a magnetic field. Galaxy clusters support magnetic fields of μG strength which are coherent over several kpc, and thus provide a natural place to search for photons from axion-photon conversion of the CAB.

In fact, a soft X-ray excess above the emission from the hot (~ 8 keV) intracluster medium has been observed by a number of experiments in a large number of galaxy clusters since 1996 [18], for a review see [19]. For example, the observed excess luminosity from the central 0.5 Mpc region of the nearby Coma cluster is $\mathcal{L}_{obs.excess} \approx 10^{42}$ erg s^{-1}.

From observations of Faraday rotation of polarised sources in and behind Coma, it has been argued that the typical size of the cluster magnetic field is $\mathcal{O}(B) = 1 - 10$ μG with coherence lengths ranging from 2 kpc to around 30 kpc [20].

The expected luminosity from axion-photon conversion of the CAB arising from a cylindrical volume of radius 0.5 Mpc and depth 3 Mpc along the line of sight may then easily be estimated as,

$$\mathcal{L}_{a\to\gamma} \approx 1.7 \cdot 10^{42} \times \left(\frac{\Delta N_{eff}}{0.57}\right) \left(\frac{B}{2\ \mu\mathrm{G}} \frac{10^{13}\ \mathrm{GeV}}{M}\right)^2 \left(\frac{L}{1\ \mathrm{kpc}}\right) .$$

Thus, the observed soft X-ray excess appears to easily be accommodated by axion-photon conversion in the cluster magnetic field. This conclusion holds also away from the small-angle approximation, as shown in [8]. A more detailed study of the morphology of the expected excess flux from the Coma cluster will appear in future publications.

This scenario makes several additional predictions. As the CAB is uniformly distributed, the produced luminosity is determined only by the magnetic field and the electron density, and is independent of the cluster temperature or matter distribution. The model predicts that the soft excess should be largest in cluster regions with large magnetic fields and small electron densities, and its spatial extent should be coterminous with the magnetic field. Furthermore, since the production of the soft excess is non-thermal, it should not be possible to associate any thermal emission lines to the soft excess. Moreover, the CAB axions are redshifting, and used to be more energetic by $(1+z)$ and more dense by $(1+z)^3$. It is then a prediction that the energy scale of the soft excess should grow as $(1+z)$ and, if other aspects of cluster physics are identical, the overall energy in the soft excess should grow as $(1+z)^4$.

In sum, axionic dark radiation constitute a well-motivated extension of standard cosmology, and some of the best studied string theory models predict a present day primordial background of relativistic axions with energies in the $E_a \sim 0.1 - 1$ keV range. This CAB may be detected through axion-photon conversions in magnetic fields, and may in fact already be visible through the long standing soft excess in galaxy clusters.

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